A CORRELATION STUDY OF THE SMITH TRIAXIAL (CLOSED SYSTEM) AND THE CONVENTIONAL TRIAXIAL (OPEN SYSTEM) METHODS OF ASPHALT MIX DESIGN

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Thomas Harold Espy, Jr.

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A CORRELATION STUDY OF THE SMITH TRIAXIAL

(CLOSED SYSTEM) AND THE CONVENTIONAL TRIAXIAL (OPEN SYSTEM)

METHODS OF ASPHALT MIX DESIGN

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

Figure | Page

SUMMARY

It was the purpose of this research to determine the correlation existing between the values of the angle of internal friction and cohesion of bituminous coated aggregate specimens by two separate triaxial tests so that a more unified approach to bituminous pavement stability and design could be developed.

The form of mixtures containing mineral aggregates and bituminous binders is changed by flow, and a certain resistance to the deforming force is maintained throughout the deformation. This resistance is due to two factors, partly to the frictional resistance and interlocking of the aggregate and in part to the shear resistance of the binder. Otto Mohr's theories of stress and rupture offer a mathematical explanation of these resistances in terms of the angle of internal friction (Ø) and cohesion (c).

Seventy-two test specimens were made. Their contents ranged from a coarse graded aggregate with asphalt contents of 4, 5, and 6 per cent to a dense graded aggregate with asphalt contents of 6, 7, and 8 per cent. Each variation of aggregate and asphalt content was made in triplicate so that sufficient and reliable data could be obtained.

The Smith Triaxial or closed system test required that a vertical load in two hundred fifty pound increments be applied to each specimen up to a maximum of five thousand pounds at a rate of deformation of 0.1 inch per minute. Simultaneous readings of vertical load in pounds and lateral pressure in psi were recorded as each increment was applied. This was enough information to determine the angle of internal friction and cohesion. The specimen was returned to its original height.

The conventional triaxial or open system test was made at a constant lateral pressure (10, 30, or 60 psi on the dense mix and 10, 20, or 40 psi on the coarse mix) with a vertical load being applied at a rate of 0.1 inch per minute. Simultaneous readings of the vertical load in pounds and the deflection dial in 0.001 inches were recorded at sufficient increments to obtain reliable values of cohesion and internal friction.

Sufficient weights and measurements were taken on both tests to make a bulk density analysis.

The values of cohesion and the angle of internal friction were higher when tested by the open system than when tested by the closed system. This variation should come from the difference in testing methods. The open system results were higher than the closed system results on unit weight, and bulk density. They were lower than the closed system results on per cent voids in total mix. Any variation in these results can be attributed to the fact that the closed system specimen had been deformed prior to its density and voids analysis.

The results also indicate a similarity in behavior of the materials when they are subjected to the two different tests. For this reason it must be stated that the two systems can be correlated even with the slight variation in values.

CHAPTER I

INTRODUCTION

This research is concerned with determining the values of the angle of internal friction and cohesion of bituminous coated aggregate specimens by two separate triaxial testing methods: the Smith Triaxial Test, a closed system test, and the Conventional Triaxial Test, an open system test.

It is the purpose of this research to determine the correlation existing between the values obtained by the two separate tests so that a more unified approach to bituminous pavement stability and design can be developed. The cohesion (c) and the angle of internal friction (Ø) obtained from the tests will be evaluated and correlated for this purpose.

Considerable work was done in the 1930's and early 1940's on bituminous pavement design procedure. Most of these procedures were developed on an empirical basis and test conditions had very little correlation to actual field conditions. These procedures required frequent modification and were inadequate to encompass all conditions and materials found in the field. A unified approach to the problem will be developed when a more rational analysis of the problem has been made.

The triaxial procedure is rational as it is based upon theory and experience while other procedures are based only on experience. This makes them more empirical in nature. The triaxial approach simulates actual field conditions whereby support is afforded a material under a loaded area by the surrounding material.

Very little work has been done in an attempt to correlate these two triaxial testing methods. Hennes and Wang (1) tested several specimens using iron washers as coarse aggregate in a matrix of sheet asphalt composition. One specimen was tested in a closed cell while several other specimens were tested in an open cell. Results showed a higher cohesion and smaller angle of internal friction in the closed system. Smith (2) reports that at low lateral pressures there is poor agreement between the two methods. However, at higher lateral pressures where the closed system data assume straight-line characteristics the two methods of test give very comparable results. It must be pointed out that information is very limited in both these cases.

CHAPTER II

TRIAXIAL TESTING

General.--The word "triaxial" is applied to a mechanical test whereby a load is applied vertically to a cylindrical specimen while a lateral supporting pressure is being applied to the specimen, usually by means of some fluid. A special case of this triaxial test is a simple compression test in which the lateral supporting pressure is zero. The cohesion and the angle of internal friction are found from relations that exist between the vertical load and lateral supporting pressure.

In mixtures containing mineral aggregates and bituminous binders, no sharp rupture or sudden change occurs under ordinary conditions of loading. The form of the material is changed by flow and a certain resistance to the deforming force is maintained throughout the deformation. This resistance is due to two factors, partly to the frictional resistance and interlocking of the aggregate and in part to the shear resistance of the binder which is termed cohesion.

Frictional resistance increases in proportion to the load applied transversely to the shearing plane or planes. Viscous resistance increases with the speed of shearing (3).

The mathematical theories explaining these resistances most generally accepted are Mohr's theories of stress and rupture.

The Triaxial Test and Mohr Theories.--Otto Mohr, a German physicist, developed a procedure for determining stress conditions on any plane perpendicular to the intermediate principal plane. His procedure was derived by the laws of statics and applies to bituminous materials as well as other materials. Although the original derivation applied to cubes, it applies equally as well to cylinders.

The stress acting normal to the top of the specimen is σ_1 and the stress acting normal to all faces of the specimen is σ_3. When stresses on a plane consist only of normal components, then these stresses are termed principal stresses. σ_1 is called the major principal stress and σ_3 is called the minor principal stress. σ_3 acts at an angle, α, to the intermediate principal plane as shown in Figure 1. As long as these stresses remain normal to the sides of the specimen, no shear stresses will develop on these sides.

Mohr set up a set of coordinate axes where the x-distances depicted normal stresses and y-distances represented shear stresses. The coordinates of a point on the graph $(\sigma_1 \tau)$ represent a combination of shear and normal stresses regardless of the orientation of the intermediate principal plane. σ_1 and σ_3 are laid off on the normal stress axis and the difference between them, $\sigma_1 - \sigma_3$, forms the diameter of a semi-circle known as "Mohr's Circle." Other geometrical properties are shown in Figure 2(a).

An infinite number of values of σ_1 and σ_3 could be selected. If this happened, the circles of Figure 2(a) would be so close together that a straight-line would be formed similar to that in Figure 2(b).

This straight-line is known as "Mohr's envelope of rupture" and is obviously tangent to each of the circles. His theory of rupture states that failure of a material will occur on the plane represented by the point of intersection of the circle and envelope.

> "Mohr reasoned that yield or failure within a material was not caused by normal stresses alone reaching a certain maximum, but by critical combinations of both shear and normal stresses. The failure is essentially by shear, but the critical shear stress is governed by the normal stress acting on the potential surface of failure." (2)

Triaxial tests are usually run by using three lateral pressures. (5) (6). Three circles are thus formed and their common tangent represents the critical combination of normal and shear stresses to produce failure in the specimen. By knowing the location of the rupture envelope, one can find the two resisting factors in the asphalt specimen: cohesion and internal friction. They are shown graphically in Figure 3.

The angle of internal friction, Ø, is the slope of the rupture envelope and cohesion, c, is the shear stress intercept at zero normal stress. This c intercept is obtained

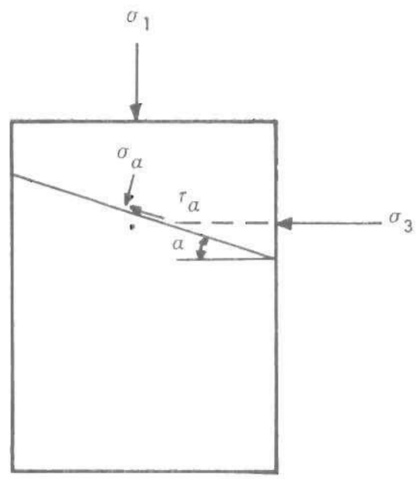

Figure 1. Stresses Developed in a Specimen.

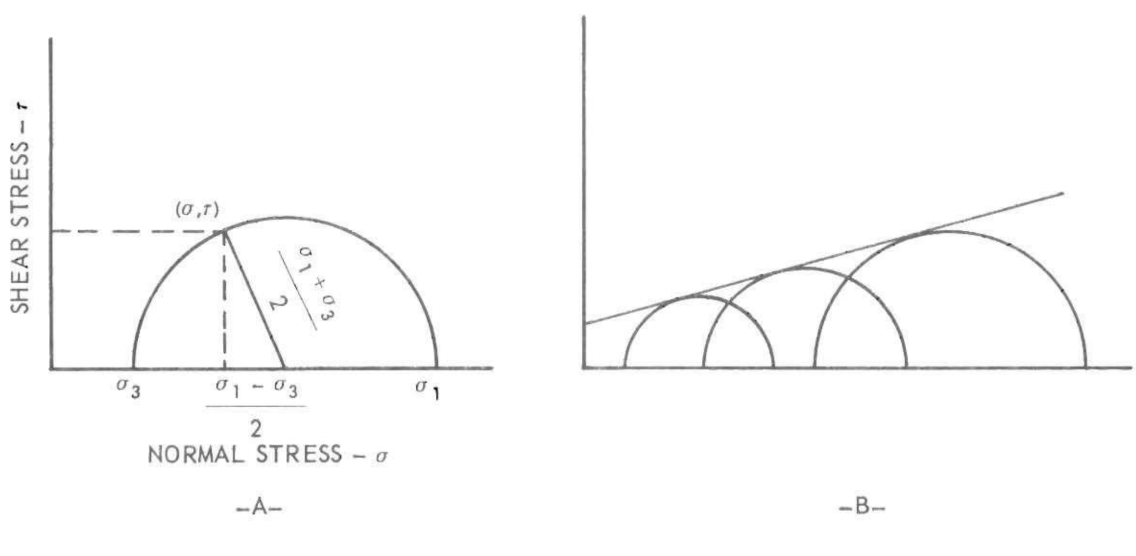

Figure 2. Mohr's Circle and Failure Envelope.

by extending the tangent portion of the rupture envelope to the y-axis. Although this method has been questioned by several people, it has been justified by McLeod (7), (6), and Holtz, Rutledge, and Nijboer (6).

The values of ϕ and c may also be determined by the application of Mohr's stress diagram and the Coulomb equation, as shown in Figure 3. McLeod (7) proved that the Coulomb envelope and the Mohr envelope were the same for identical materials. The following equation is derived from the geometry of the straight rupture envelope:

$$\sigma_1 = \sigma_3 \tan^2(45 + \phi / 2) + 2C \tan(45 + \phi / 2) \qquad (1)$$

where:

σ_1 = major principal stress
σ_3 = lateral principal stress

ϕ = angle of internal friction
c = cohesion

Derivation of the above equation yields:

$$\frac{d\sigma_1}{d\sigma_3} = \frac{a}{b} = \tan^2(45 + \phi / 2) \qquad (2)$$

where: $d\sigma_1$ = a = difference in vertical pressures
$d\sigma_3$ = b = difference in lateral pressures
$\frac{a}{b}$ = slope of vertical lateral pressure curve as shown in Figure 4

$$\phi = 2(\text{arc tan } a/b) - 90^\circ \qquad (3)$$

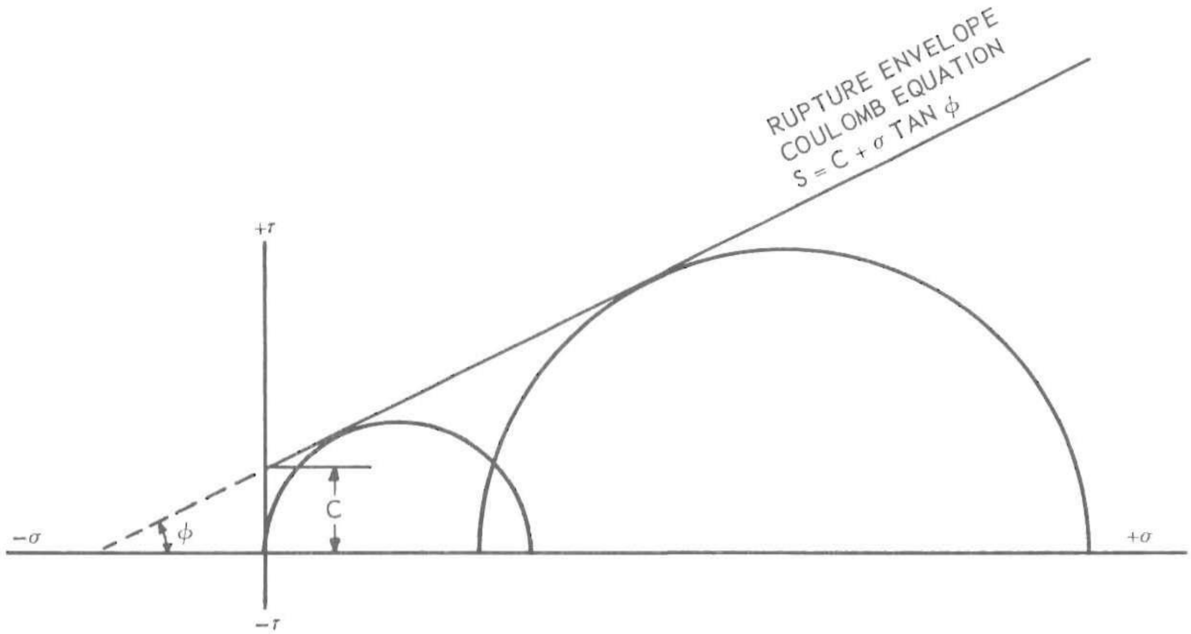

Figure 3. Coulomb Equation and Rupture Envelope.

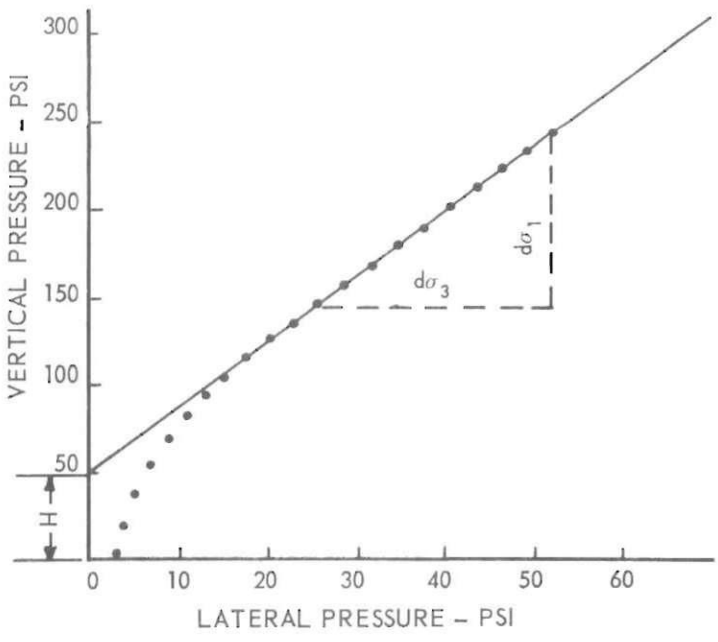

Figure 4. Vertical Pressure Versus Lateral Pressure Curve.

Solving equation (1) for zero lateral pressure yields the following equation:

$$\sigma_1 = 2C \tan(45 + \phi / 2)$$

If I is defined as the intercept of the straight-line portion of the vertical-lateral pressure curve and the vertical pressure axis, as shown in Figure 4, then:

$$C = \frac{I}{2 \tan(45 + \phi/2)} \qquad (5)$$

The value of internal friction is determined from equation (2), and the value of cohesion is determined from equation (5). (8), (2)

The Open System Method.--A sketch of the open-system triaxial method is shown in Figure 5. (6) The specimen is encased between two disks inside a rubber membrane. The lower disk is a porous stone which enables drainage of any fluid from inside the specimen and also insures atmospheric conditions inside the specimen. The rubber sleeve prevents entrance of the fluid into the sample. Lateral pressure is applied from a constant air supply and is recorded on the pressure gauge. The lateral support is obtained by transmission of the lateral pressure to the sides of the specimen by the cell fluid, and is measured in terms of pounds per unit area. This pressure is also applied to the top of the specimen,

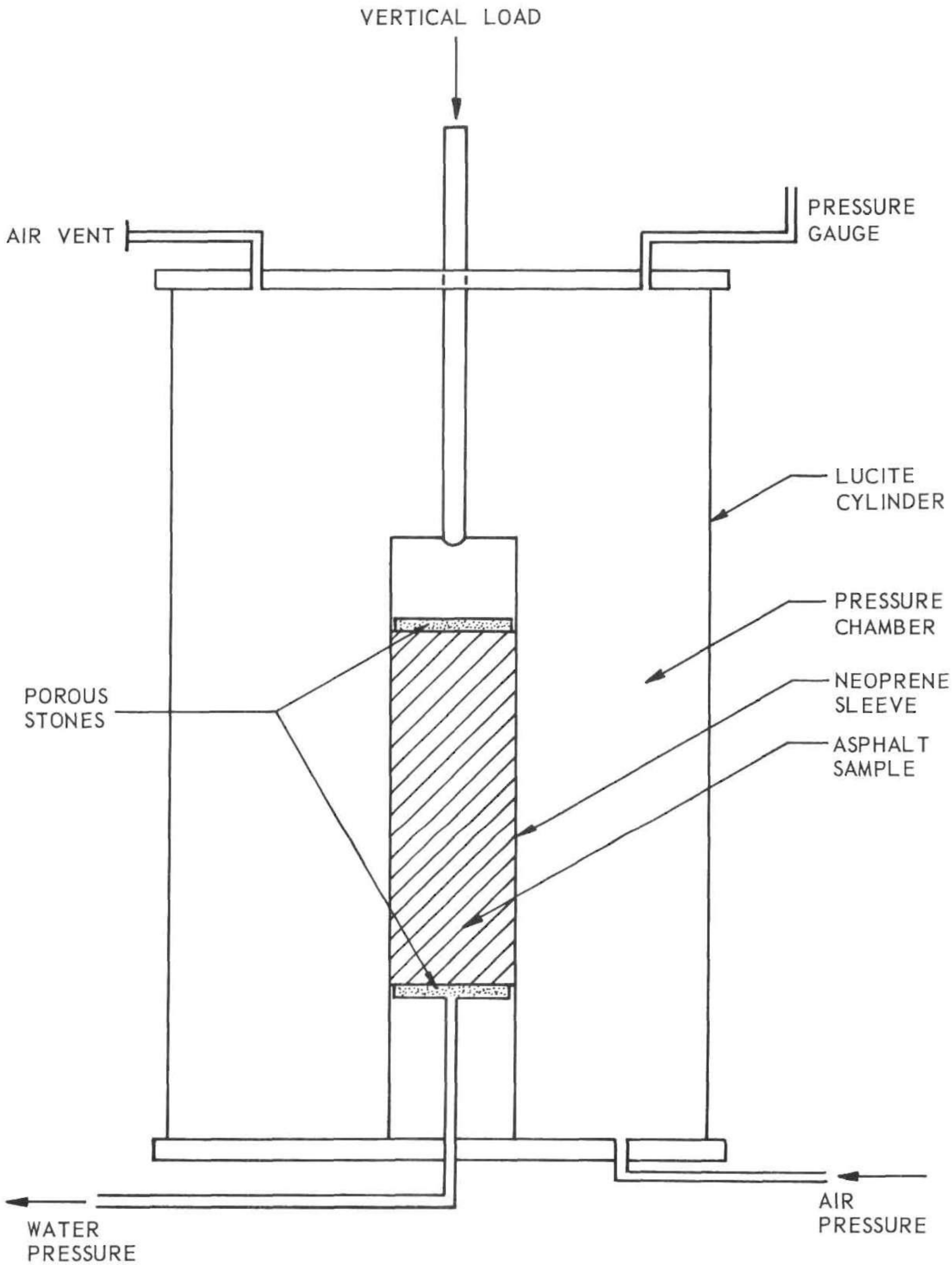

Figure 5. The Open System Method.

thereby causing a supplemental vertical load. The axial load is divided by the circular area of the specimen and the quotient is added to the lateral pressure to get the total axial pressure. (5)

The specimen is deformed at a constant rate of deformation until it fails. When it fails, the failure will occur along an inclined surface similar to aa or bb in Figure 5. The axial loads are recorded at certain deformations. This information together with the constant lateral pressure will enable a single Mohr Circle to be drawn. A set of three such tests are usually required to determine the rupture envelope and subsequently cohesion and the angle of internal friction.

The Closed System Method.--The closed system triaxial test (Smith Triaxial) (2) is shown schematically in Figure 6. (8) The specimen is placed between two perforated plates and inside a neoprene sleeve called the inner neoprene sleeve. The testing head rests on the upper plate and is partly enclosed in the inner sleeve. The neoprene sleeve and perforated plates serve the same purpose in this test as they do in the open system test. In the closed system test the specimen is confined by a liquid which in turn is confined in a rigid cell. The pressure developing within the confining liquid as a result of the lateral strain is recorded on the pressure gauge on the rigid cell. There is no vertical load other than the primary axial load being applied from

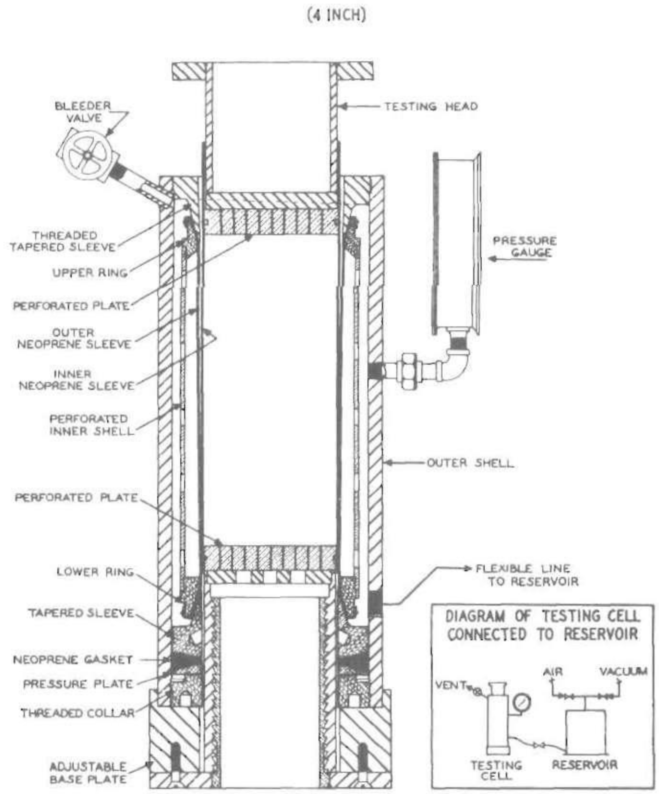

Figure 6. Closed System Method.

the compression machine.

A static load is applied to the specimen and maintained until deformation ceases and increase of lateral pressure ceases. The resulting vertical pressure and lateral pressure are then recorded. A greater static load is then applied and this procedure is repeated until enough points have been obtained so that an accurate graph, similar to the one in Figure 4, may be plotted. The application of static loads in increments eliminates the viscous resistance of the asphalt binder which is directly proportional to the rate of strain. Also, when static loads are employed the effects of temperature upon measured stability properties are small because viscous resistance has been reduced to zero. Cohesion and the angle of internal friction may be computed from formulas (5) and (2) respectively. By using the closed system method, the same fundamental properties (angle of internal friction and cohesion) can be obtained from one sample as can be obtained from three samples in the conventional open system triaxial method.

<u>The Triaxial Test Specimen</u>.--Vaughn Smith, in selecting conditions for his closed-system test (2), selected a test specimen approximately 4 inches in diameter and 8 inches in height. Several authorities agree that the test specimen should have a height-diameter ratio of two or more and a height-maximum size aggregate ratio of four or more. In a

specimen of this size, material of sizes not exceeding 1 inch can be tested with excellent results while materials having particles up to 2 inches in diameter can be tested with sufficient accuracy and reproducibility for most design purposes. The 8 inch height will eliminate the effects of interference of shear cones and friction against testing heads. The same 4 inch by 8 inch test specimen will be used for the open-system test so that correlation can be obtained between the two systems.

An accurate testing procedure of bituminous mixes involves the preparation of test specimens of densities and gradations that closely correlate field conditions. Studies have shown that static, double plunger, and impact hammer compaction do not reproduce actual construction conditions. Construction compaction by rolling enables the particles to move into place along the lines of least resistance and orient themselves in such a way that the larger particles are not forcibly interlocked at their points. Hveem and other members of the Triaxial Institute have designed a kneading machine that works on the following principle:

"The material is fed into a rotating mold and kneaded into place by a tamping foot of the general shape of a slice of pie with rounded corners." (3)

This foot descends with a rather slow motion in order to avoid impact, and has a short dwelling period at the bottom of the descent to overcome viscosity. It operates under a constant load, the low point of the descent being automatically raised as the material rises in the mold. The specimen is finished off by a static load when completed.

Members of the Triaxial Institute have made some comparisons between kneading compaction, Marshall drop hammer compaction, and normal double plunger static compaction (9). The results are shown in Figures, 7, 8, 9, 10. It can be clearly seen that the kneading compactor will give more realistic results. For the above reasons, the kneading compactor was chosen for these tests.

The test specimens were compacted to a density that approximated an average of initial densities on ten construction jobs in the State of Georgia. (10) The detailed compaction procedure for obtaining uniform density was taken from work done by Dr. Donald O. Covault of the Georgia Institute of Technology in his continuation of Reference (10).

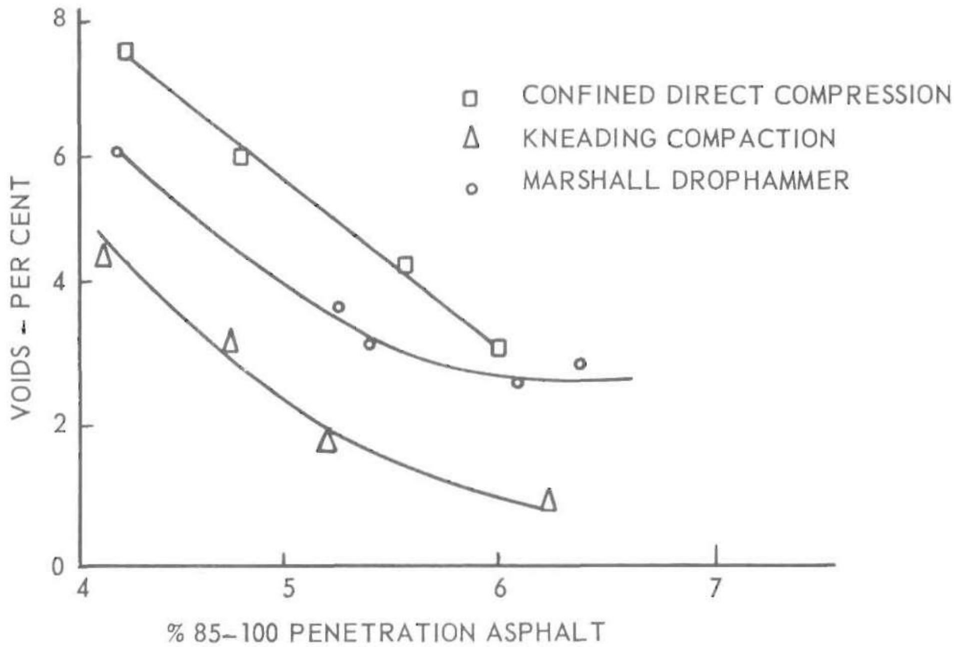

Figure 7. Voids as Affected by Types of Compaction.

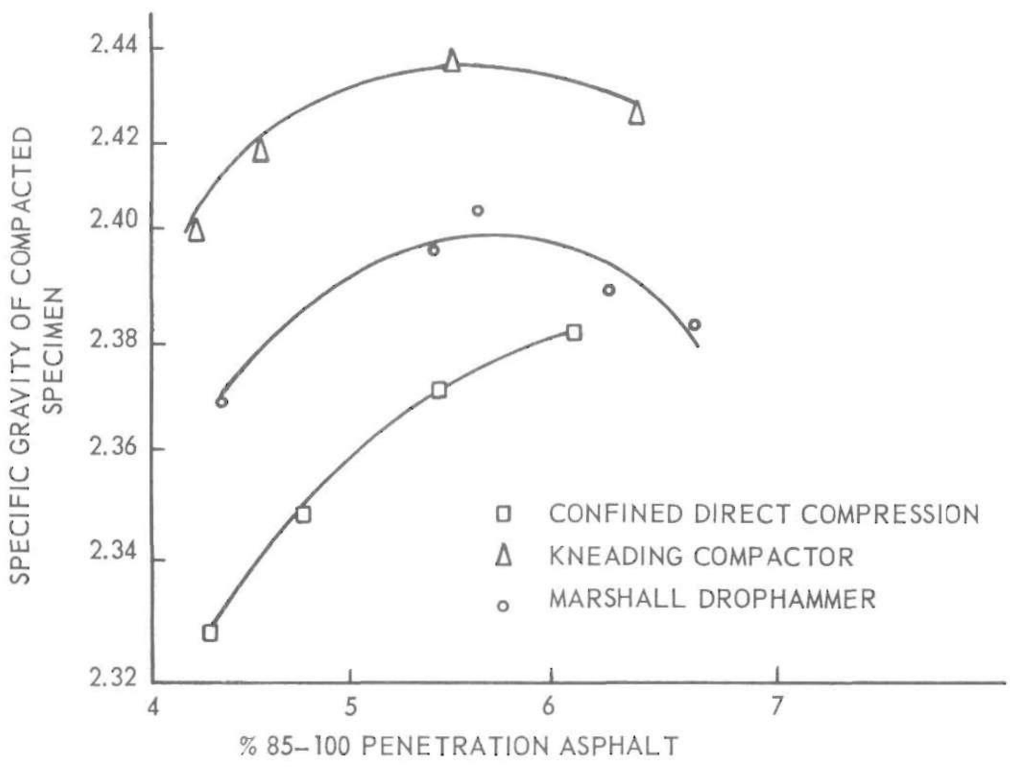

Figure 8. Specific Gravity as Affected by Types of Compaction.

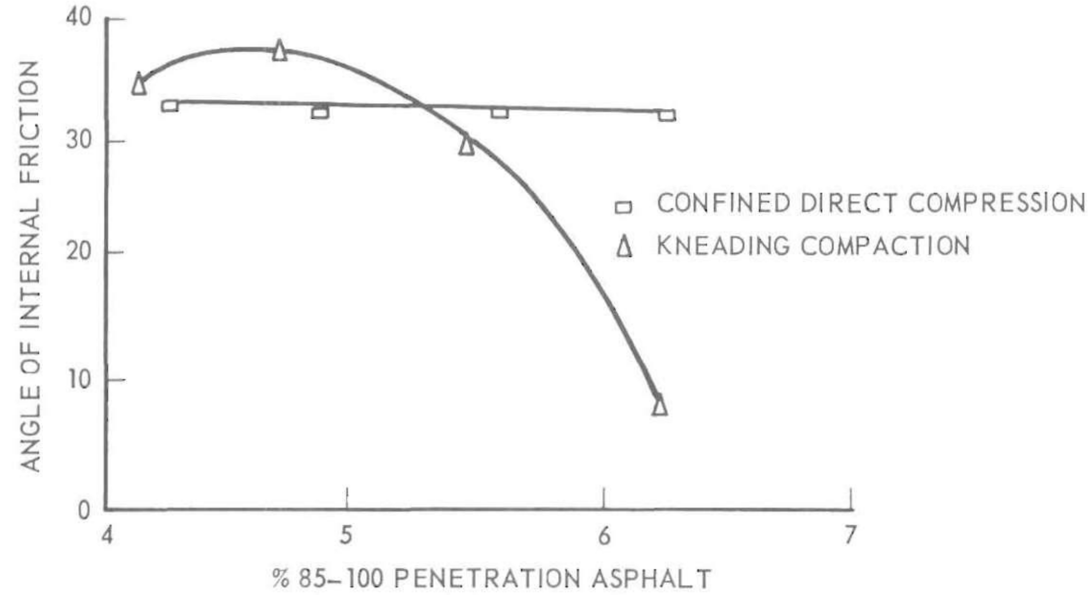

Figure 9. Angle of Internal Friction as Affected by Compaction.

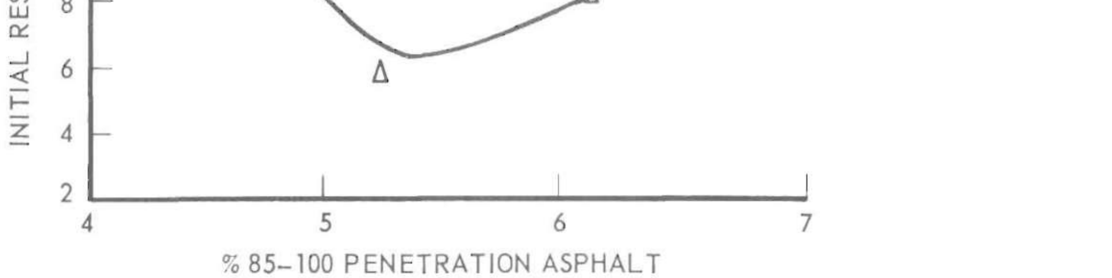

Figure 10. Initial Resistance as Affected by Type of Compaction.

CHAPTER III

MATERIALS AND EQUIPMENT

Materials.--A crushed stone from Stockbridge Stone Company, Stockbridge, Georgia, was used as the aggregate. The asphaltic concrete binder course "type B", as designated by the Georgia State Highway Department, contains approximately 55 per cent of size sixty-seven stone and 45 per cent of stone screenings. The asphaltic concrete surface course "type E" contains approximately 25 per cent of size seven stone and 75 per cent of stone screenings. Exact gradation of the two mixes is shown in Figure 11. The bulk specific gravity of this stone is 2.629. The bituminous material used was a paving grade of asphalt cement (AC-8) with a penetration of 85 to 100 at 77° F and a specific gravity of 1.025 at 77° F.

Equipment.--The batching equipment included scoops, storage pans, metric weights, and scales (Figure 12). The scales were Ohaus Micrometer scales of five thousand gram capacity and were correct to the nearest 0.5 gram.

A Hobart mechanical mixer of ten quart capacity was used to mix the material. This mixer, with bowl, paddle mixing blade, and wire mixing blade, is shown in Figure 13. The bituminous mix is transferred from the mixer to the

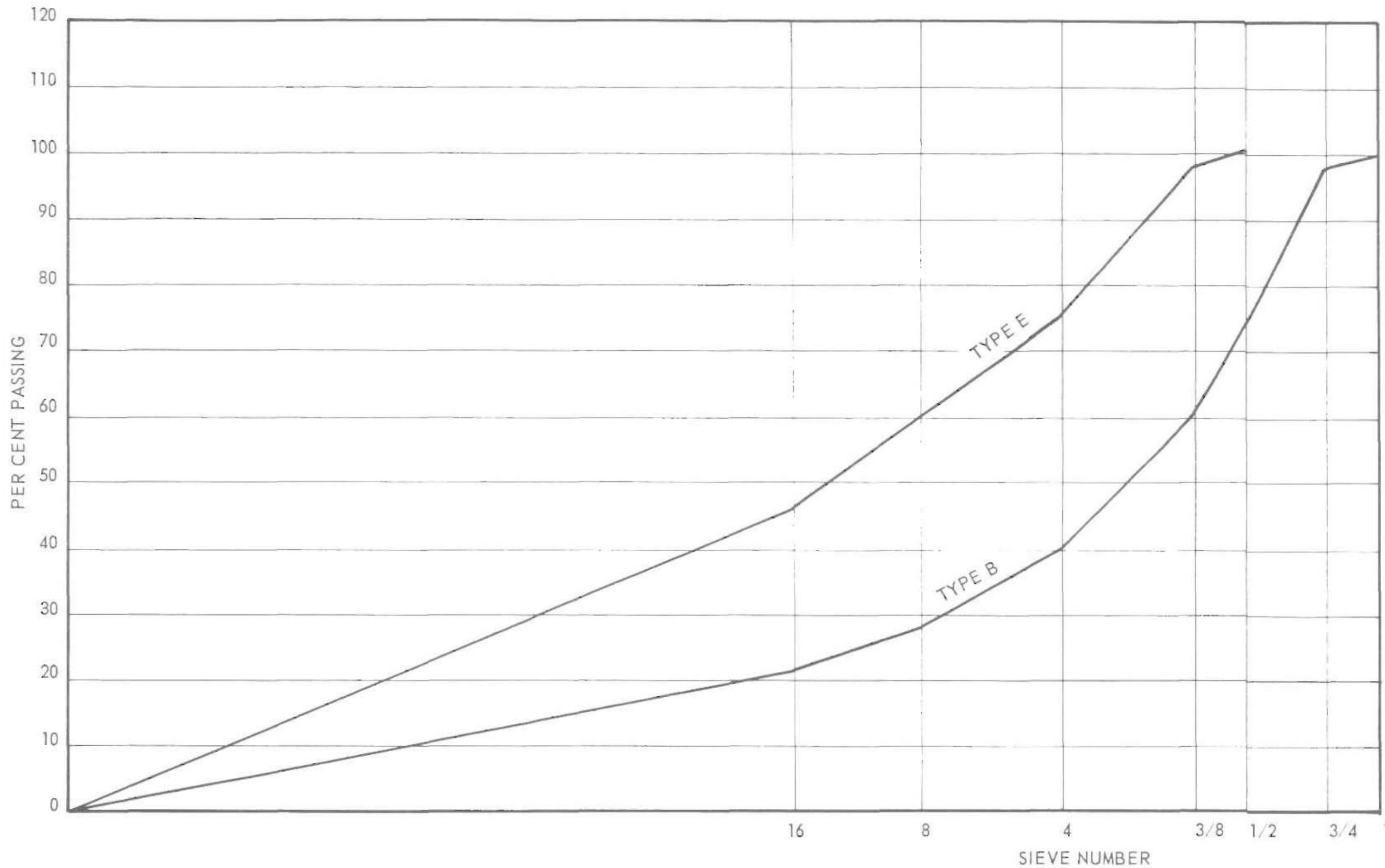

Figure 11. Aggregate Gradation.

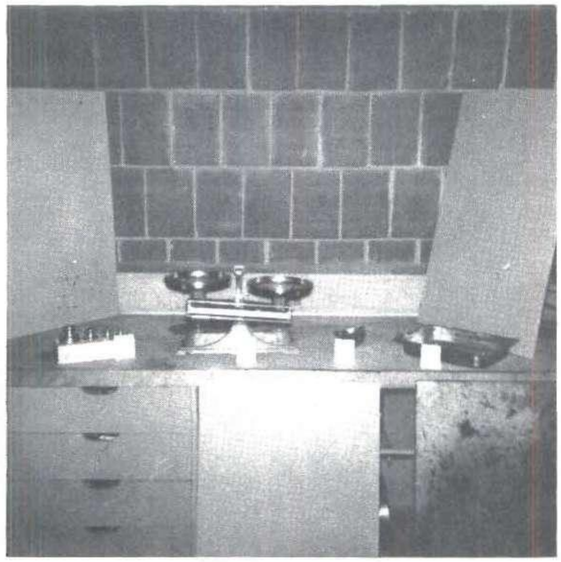

Figure 12. Batching Equipment.

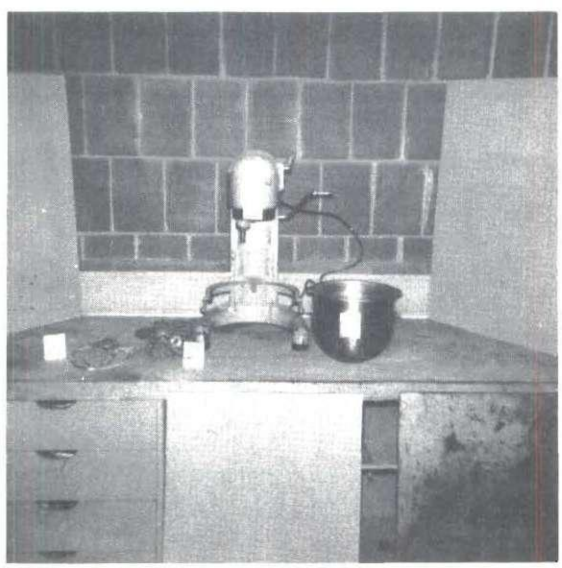

Figure 13. Mixing Equipment.

compactor by means of eight 1-inch by 2-inch by 12-inch aluminum sleeves (B in Figure 14). A sleeve holder (A in Figure 14) and trowel are also needed to insure an even distribution of mix in each of the eight aluminum sleeves.

The compaction is done by a kneading compactor manufactured by Soil Test, Inc., of Chicago, Illinois (B in Figure 15). Figure 15 also shows the positioning of the aluminum sleeve, the positioning of the mold and mold holder, the timer, and the trowel used to push the material from the sleeve into the mold.

The open system cell (Figure 16) was designed and built by personnel of the Georgia Institute of Technology. The lucite cylinder has a depth of eighteen inches and a diameter of twelve inches, thereby insuring a four inch diameter band of air around the sample at all times. The cell is equipped with a pressure gauge with an accuracy of $\pm$ 0.5 pounds per square inch to measure the lateral support pressure. The lateral pressure is applied from a regulated air supply. The deformation is recorded on a micrometer dial gauge connected to the compression machine and is measured to the nearest 0.001 inch.

The closed system cell was built by personnel of the Georgia Institute of Technology Engineering Experiment Station. This apparatus is shown in Figure 17. The main cell has a chamber of twelve inch depth and is slightly over

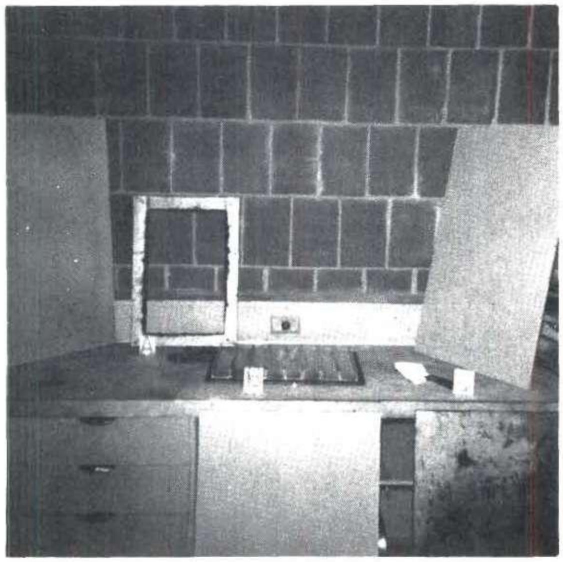

Figure 14. Transfer Sleeves and Sleeve Holder.

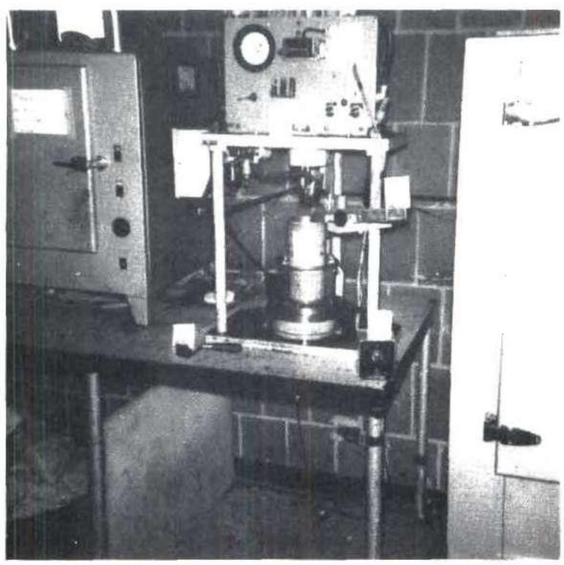

Figure 15. Kneading Compactor.

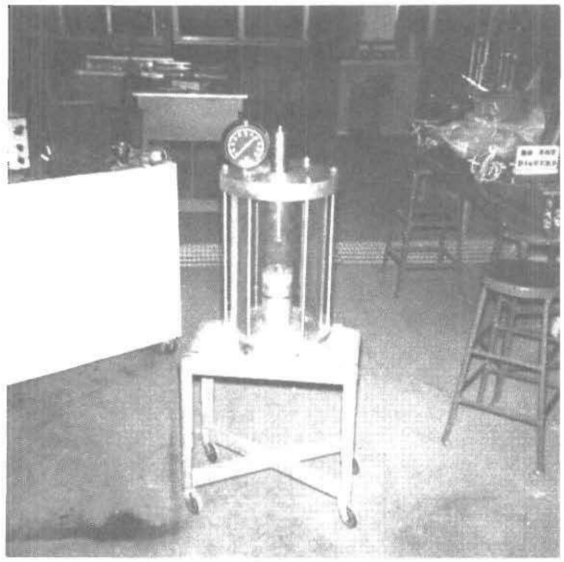

Figure 16. The Open System Cell.

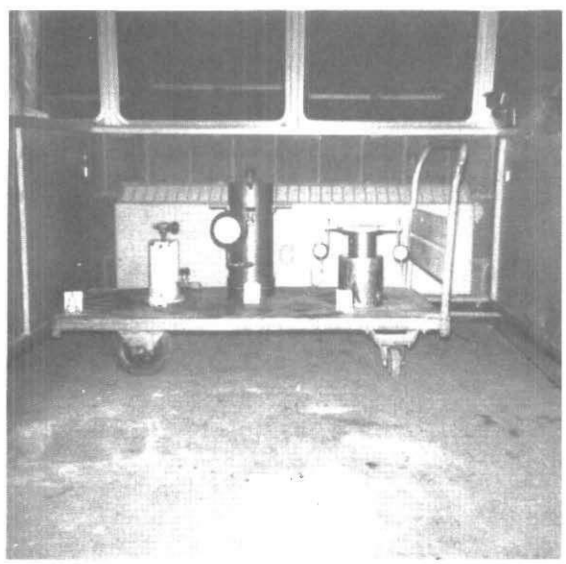

Figure 17. The Closed System Apparatus.

four inches in diameter. Two valves are attached to the cell. These valves are used for the entrance and exit of water and for the application of vacuum needed to insure an air-free chamber. The lateral pressure is recorded on a pressure gauge of $\pm$ 0.5 pounds per square inch accuracy. The testing head is placed on top of the specimen. Deformation is recorded from dial gauges of $\pm$ 0.001 inch accuracy attached to the testing head and resting on the "ears" of the main cell. A water hose and a vacuum apparatus are needed to complete the assembly.

A Tinius-Olsen Testing Machine of twenty thousand pound capacity (Figure 18) applied the loads for all tests. The load was applied at a constant deformation and data was recorded to the nearest five pounds.

Three constant temperature ovens similar to the one in Figure 19 maintained the desired temperatures to an accuracy of $\pm$ 2^{o} F. Each oven was set at either 140^{o} F., 230^{o} F., or 300^{o} F., and this temperature was maintained throughout the period of testing. Gas burners were used to dry the aggregate prior to gradation and a Gilson Mechanical Testing Screen (Figure 20) was used to sort the aggregate according to size.

The plungers shown in Figure 21 are required to place the seating load on the specimens.

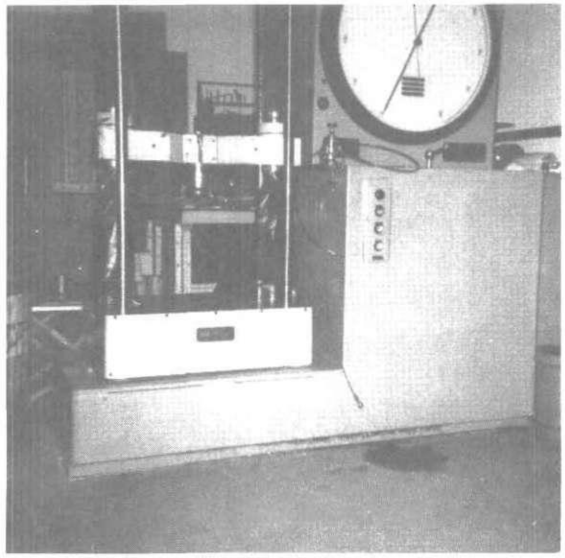

Figure 18. Tinius-Olsen Testing Machine.

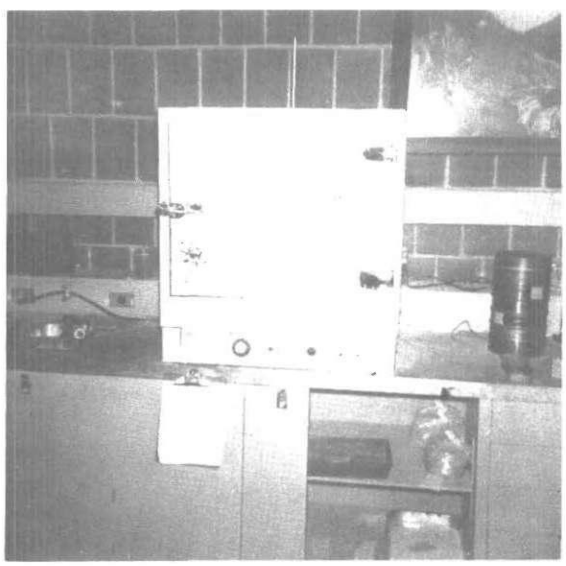

Figure 19. Oven.

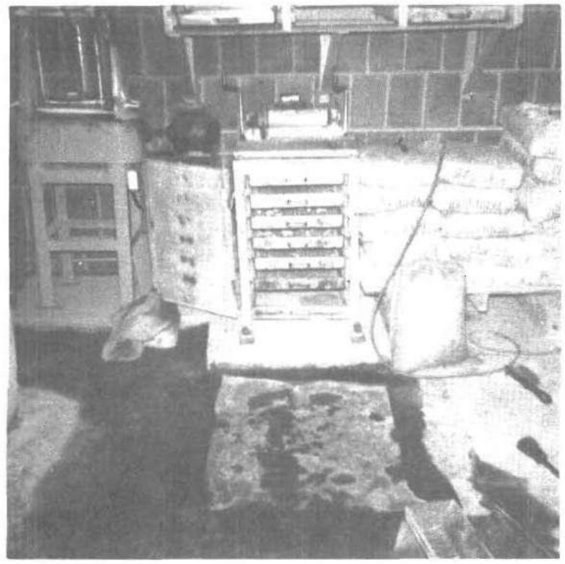

Figure 20. Gilson Mechanical Testing Machine.

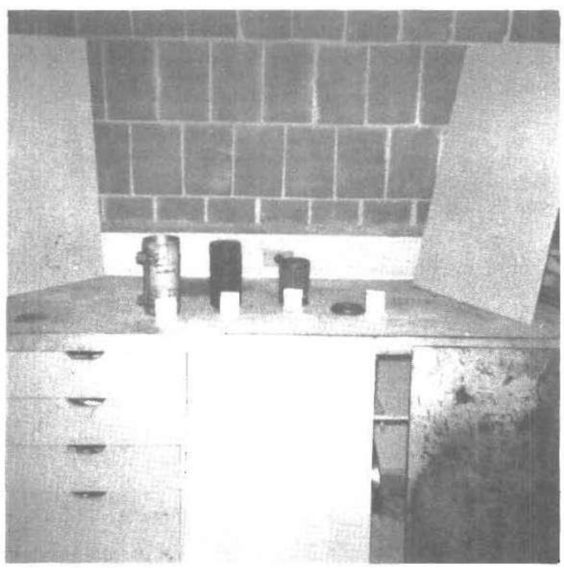

Figure 21. Mold, Specimen, and Plungers.

CHAPTER IV

PROCEDURE

General.--Triaxial specimens were made using two separate aggregate gradations. A coarse graded aggregate similar to the asphaltic concrete "type B" binder course as designated by the Georgia State Highway Department was batched, mixed, and compacted with asphalt contents of 4, 5, and 6 per cent by weight of total sample. A dense graded aggregate similar to the asphaltic concrete "type E" surface course was batched, mixed, and compacted with asphalt contents of 6, 7, and 8 per cent by weight of total sample. Each specimen of different asphalt content and gradation was made in triplicate so that sufficient and reliable data could be obtained. Enough data was obtained to calculate density, unit weight, per cent voids in total mix, cohesion, and the angle of internal friction.

Aggregate Preparation and Batching.--The aggregate was dried in a gas oven at 235° F. until all moisture had been removed. It was then placed on the mechanical screen and divided into sizes by material retained on the 3/4 inch, 1/2 inch, 3/8 inch, numbers 4, 8, and 16 screens and pan. The correct gradation and weight of aggregate to insure that the height and density of the samples conformed to the requirements of Chapter II had been predetermined by Dr. D. O. Covault of the Georgia Institute of Technology. The gradation is shown in Figure 11, and the correct batch weights for various asphalt contents are shown in Appendix I. Each specimen was batched and placed in a 300° F. oven.

Mixing.--Each batched specimen was allowed to remain in the 300° F. oven overnight. The specimen was then removed from the oven, placed in the mixing bowl, tared on the micrometer scales, and a predetermined amount of asphalt was added by weight. The sample was mixed in the mechanical mixer until a uniform mix was obtained. The "type E" mixes were mixed with the paddle blade to insure greater movement of all particles. The "type B" mixes were mixed sufficiently with the wire whip. A small amount of hand mixing was required to see that no part of the bituminous mixture adhered to the bowl. Following the mixing, eight aluminum sleeves were lined up and held secure by the sleeve holder. The mixture was then heaped on the sleeves and was spread evenly in each of the eight sleeves by means of a trowel. The eight sleeves were then placed in an oven until the temperature of the mix reached 230° F.

Compaction.--When the mixture reached 230° F. it was ready for compaction. The exact compaction procedure used to obtain the desired density had been determined by research being supervised by Dr. D. O. Covault of the Georgia Institute of Technology. The compaction was achieved by 110 blows of the kneading compactor at 89.9 psi foot pressure and 15 blows at 44.5 psi foot pressure, all 125 blows having a dwell time of 0.40 seconds. The mixture was fed into the mold and compacted according to the schedule shown in Table 1. Each sleeve was removed from the oven separately and when all eight sleeves had completely filled the mold with the bituminous mixture, the mold and mold holder were released from the turntable and the specimen was removed from the mold by loosening the restraining bolts. The specimen was then placed in a 140^{o} F. oven and allowed to stabilize at that temperature. The minimum length of time for this stabilization was 4 hours but the specimens usually were allowed to remain in the oven overnight. The specimen was then removed from the oven, placed back in the split mold, and the mold's restraining bolts were tightened. A seating load was then applied to the specimen while the specimen was still at 140^{o} F. and released immediately. This seating load was in the magnitude of five hundred psi and was applied at the rate of 0.25 inch per minute.

Table 1. Schedule of Compaction Blows for 4-Inch Diameter Specimen

Sleeve No.	Odometer Reading	Portion of Sleeve to be Placed in Mold at One Time and Corresponding Number of Blows	Foot Pressure
1	0-10	1/3 @ 3 + 1	89.9
2	10-25	1/7 @ 2 + 1	89.9
3	25-40	1/7 @ 2 + 1	89.9
4	40-54	1/7 @ 2	89.9
5	54-68	1/7 @ 2	89.9
6	68-82	1/7 @ 2	89.9
7	82-96	1/7 @ 2	89.9
8	96-110	1/7 @ 2	89.9
	110-125	1/7 @ 2	44.5

Following the completion of the compaction procedure the specimen is allowed to remain at room temperature (75^{o}F) until it is ready to be tested.

Bulk Density Determination.--In the open system a specimen is loaded to failure while in the closed system the specimen is loaded to a point just less than failure. The load on the specimen in the open system test is reduced at a rate of 0.1 inches per minute to the point where the specimen reaches its original height. If the decrease in vertical load is not enough to cause this return to original height, a lateral pressure must be applied. The bulk density of the closed system can then be accurately determined by the use of paraffin (Appendix II). The determination of the bulk density of a specimen used in the open system is more difficult. Since the sample is loaded to failure, the bulk density must be determined prior to the stability test. The open system method will employ an uncoated sample because in the closed system the specimens are tested without a coating of paraffin. This procedure is established to insure comparable results and to bypass any effects that the paraffin might give to the strength characteristics of the specimens. This means a correlation must be established between the bulk densities obtained from coated and uncoated specimens.

Results of bulk density tests on samples of the dense aggregate gradation (type E) coated with paraffin showed no appreciable variation from results obtained from tests on similarly graded uncoated specimens. However, there is some variation of results on tests performed on coated and uncoated samples of the coarse graded mix (type B). This is due to greater number of surface voids found in the coarser mix. These results, shown in Table 2, are averages of three specimens of each asphalt content. The conversion factor is added to the bulk density of each sample so that comparable results are obtained for type B specimens.

Bulk densities were determined from procedures set forth by the Asphalt Institute (8). A detailed account of bulk density and voids analysis procedure is found in Appendix II.

The Closed System Test.--The vacuum apparatus was attached to the upper valve on the Smith cell and a vacuum applied until all the water and air inside the cell had been withdrawn. The height and diameter of each specimen was then measured and recorded and the specimen was then placed inside the cell between two porous plates. The water hose was attached to the lower valve and water was allowed to enter the cell at a rate low enough to prevent any development of a lateral pressure. Care was taken to see that no air entered the cell. When a steady rate of flow with no air bubbles came out of the top valve, the vacuum was removed and the valves were turned off in such a manner that the cell remained completely full of water and free of air. The water hose was then attached to the water reservoir. The testing head was placed on the top porous plate and the micrometer dial gauges were zeroed. This entire apparatus was then centered on the Tinius Olsen testing machine and the upper table of the testing machine was lowered until it was flush with the testing head of the Smith cell. An initial lateral pressure of two psi was applied to the specimen, the micrometer dial gauges were checked to see if they needed rezeroing, and the appropriate scale on the testing machine was zeroed. The specimens were then loaded in two hundred fifty pound increments up to a maximum of five thousand pounds at a rate of deformation of 0.1 inch per minute.

A two hundred fifty pound increment was applied and the machine was stopped until the rate of deformation of the sample was less than 0.001 inch per minute, at which time simultaneous readings of vertical load in pounds and lateral pressure in psi were recorded. This procedure was repeated twenty times. The specimen was brought back to its original height by raising the upper table of the testing machine at a rate of 0.1 inch per minute and applying a lateral pressure until the dial gauges reached zero. A vertical pressure versus lateral pressure curve was plotted from the data that had been obtained and values of cohesion and the angle of internal friction were computed.

Table 2. Bulk Density Conversion for Type B Mix

Per Cent Asphalt	Conversion Factor
4	-0.103
5	-0.089
6	-0.025

The Open System Test.--The test specimen was placed on the lower porous plate and the upper porous plate and cap were placed on top of the specimen. The neoprene sleeve was then placed around the specimen and was made air tight by the application of rubber bands to the assembly. The lucite cylinder and chamber top were then assembled in such a way as to insure an air tight chamber. The entire assembly was then centered on the Tinius Olsen testing machine and the upper table was lowered until it was flush with the shaft that transmits the load from machine to specimen. The air pressure was applied to the specimen and regulated so that the pressure gauge on the chamber top indicated the desired lateral pressure (10, 30, or 60 psi on the "type E" mix, and 10, 20, or 40 psi on the "type B" mix). The micrometer dial gauge was zeroed as was the appropriate scale on the testing machine and the specimen was then deformed at a rate of 0.1 inch per minute. Simultaneous readings of the vertical load in pounds and deflection dial in 0.001 inches were recorded at sufficient increments to plot a well defined stress strain curve.

Computations.--Values for the angle of internal friction (Ø) and cohesion (c) were computed for each test specimen. A detailed account of these calculation procedures is given in Appendices III and IV.

CHAPTER V

SUMMARY OF RESULTS

The results shown in Table 3 and Figure 22 indicate a higher cohesion factor in the open system when compared to the closed system. The cohesion factor varies on a convex upward curve in both systems and the difference in values of cohesion obtained by the two systems is relatively uniform for each different asphalt content. The gradation of the aggregate did not affect the value of cohesion obtained on either the closed system test or the open system test. The convex upward curves were maintained with about the same difference in values of cohesion between the two systems for the "type B" mix and the "type E" mix.

Study of Table 3 and Figure 23 shows that the angle of internal friction of the specimens is higher when obtained by the open system than when it is obtained by the closed system. The angle of internal friction is represented by convex downward curves. The difference in values of ϕ obtained by the two tests remains uniform as the asphalt content and aggregate gradation are changed.

There seems to be no indication of the increase of the open system method over that of the closed system method due to aggregate gradation or asphalt content. Since the specimens used in both tests were made by the same procedure, any variation in results should come directly from the difference in testing methods. According to Smith (2), it is necessary to apply static loads in increments and test at zero deformation in order to overcome the viscous resistance of asphalt binder and the effects of temperature. This would affect the values obtained by the open system method because the load is applied at a continuous rate of deformation. It must be pointed out that some variation could come from personal error in determining the location of the tangents to the Mohr stress circles and to the graph depicting vertical pressure versus lateral pressure (Figure 4).

The values of unit weight, per cent voids in total mix, and bulk density are shown in Table 4 and Figures 24 and 25. In every case, except the asphaltic concrete type "E" mix with eight per cent asphalt, the open system results were higher than the closed system results on unit weight and bulk density. The open system results were lower than the closed system results on per cent voids in total mix. Any variation in these results can be attributed to the fact that the closed system specimen had been deformed prior to its density and voids analysis. This deformation caused a rearrangement of particles in the specimen or greater volume than was found in the original specimen. As the specimen was

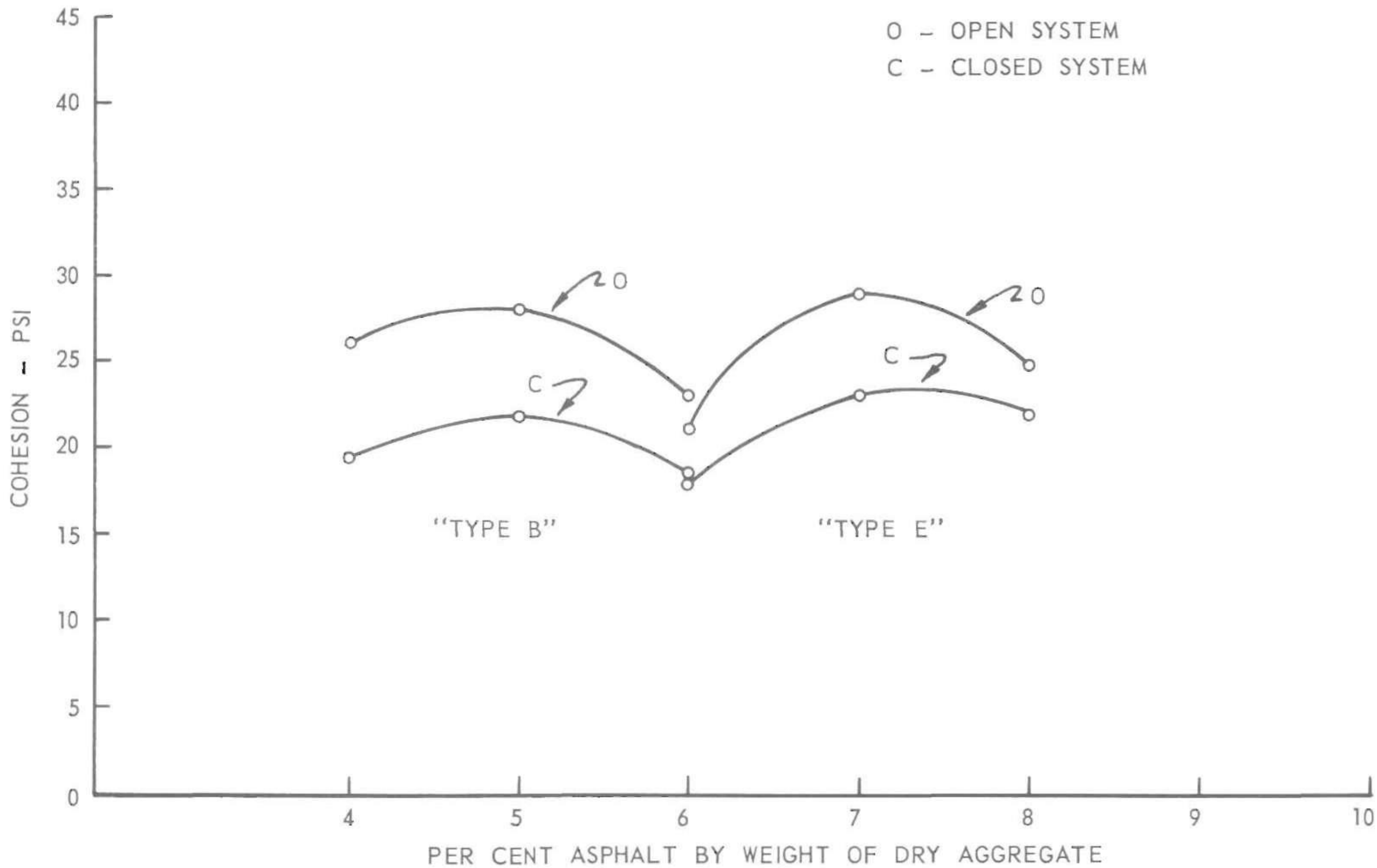

Figure 22. Cohesion Versus Percent Asphalt.

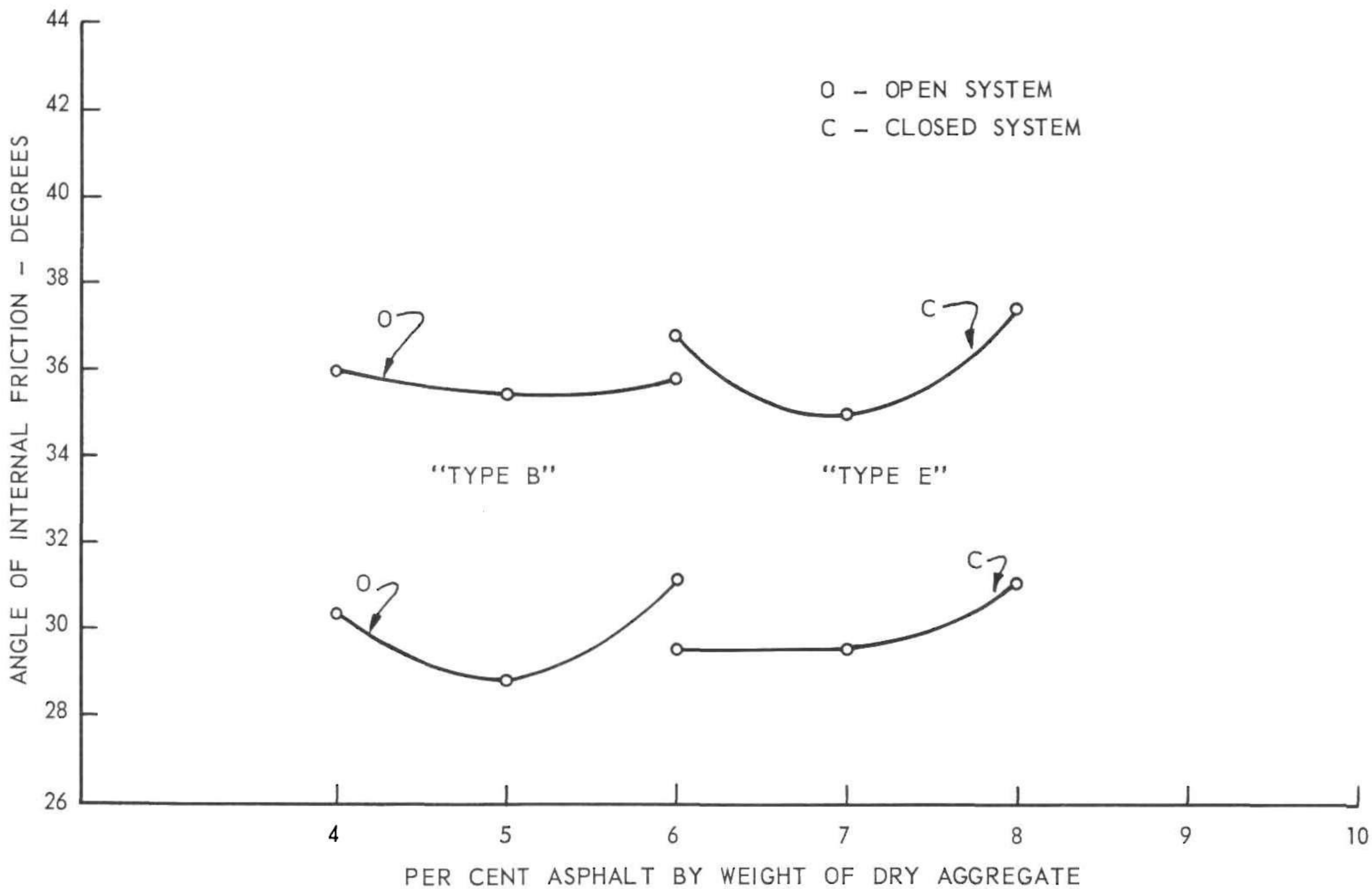

Figure 23. Angle of Internal Friction Versus Percent Asphalt.

being unloaded, these particles did not assume their original position and the specimen did not return to its exact original dimensions. In five of the design mixes, the rearrangement caused a less dense specimen to be formed while in the one remaining mix, a denser specimen was formed.

The results of the tests on angle of internal friction and cohesion indicate a similarity in behavior of the materials when they are subjected to the two different tests. For this reason it must be stated that the two systems can be correlated even with the slight variation in values. It must be stated that the values of unit weight, per cent voids in total mix, and bulk density could be brought closer together by coating the specimens tested in the closed system with paraffin. This would insure similarity in testing conditions. As far as tests on cohesion and the angle of internal friction are concerned, I would recommend that research be continued on the analysis of the data more than on the specific test procedure. One can not accurately say that test values can be correlated until he knows that he has made no mistakes in his factual analysis.

It must be pointed out that all six design mixes are classified as satisfactory mixes by the Smith test evaluation chart.

A time study was made on the various test procedures, although it was not a part of the original scope of this research. The results are shown in Table 5. It can be clearly seen that from the standpoint of time and economy the closed system is the most practical.

Table 3. Results of Cohesion and the Angle of Internal Friction

Type Mix	Cohesion	Angle of Internal Friction
CLOSED SYSTEM		
E-6	17.9	29.5
E-7	23.2	29.5
E-8	22.1	31.1
B-4	19.3	30.3
B-5	21.7	28.8
B-6	18.6	31.1
OPEN SYSTEM		
E-6	21.0	36.8
E-7	29.0	35.0
E-8	25.0	37.5
B-4	26.0	36.0
B-5	28.0	35.4
B-6	23.0	35.8

Table 4. Results of Bulk Density, Per Cent Voids, in Total Mix, and Unit Weight

Type Mix	Bulk Density $\frac{gms}{cc}$	% Voids Total Mix	Unit Weight #/cf
CLOSED SYSTEM			
E-6	2.110	12.22	131.50
E-7	2.150	9.28	134.36
E-8	2.265	3.21	141.15
B-4	2.186	11.64	136.41
B-5	2.220	8.93	138.55
B-6	2.254	6.07	140.67
OPEN SYSTEM			
E-6	2.136	10.98	133.38
E-7	2.166	8.61	135.14
E-8	2.230	4.58	139.10
B-4	2.224	10.12	138.76
B-5	2.223	8.80	138.74
B-6	2.260	5.23	141.02

Table 5. Time Schedule (Average of 5 Tests)

	Open System minutes	Closed System minutes
Batching	30	10
Mixing	15	5
Compacting	105	35
Testing	20	75
Total	170	125

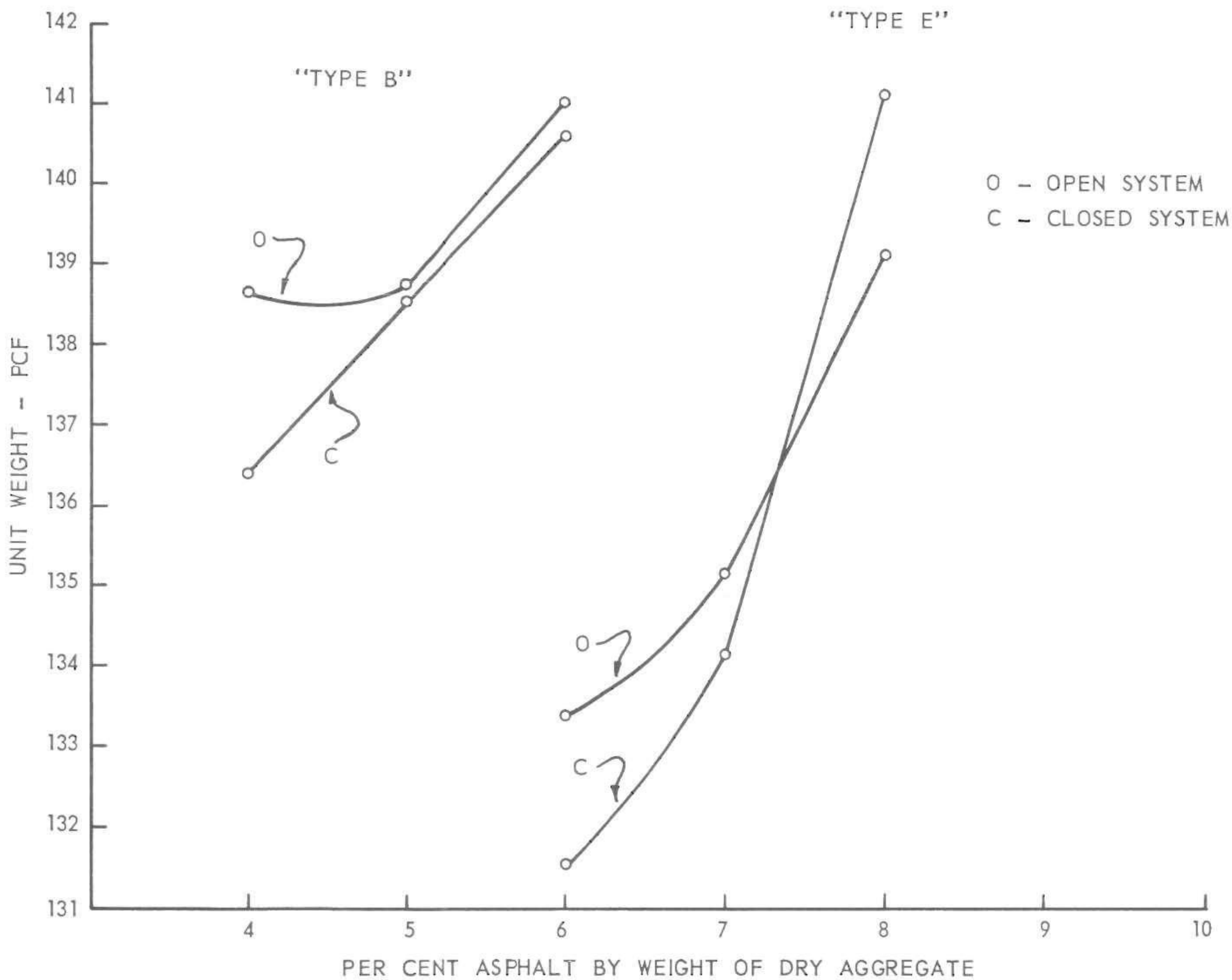

Figure 24. Unit Weight Versus Percent Asphalt.

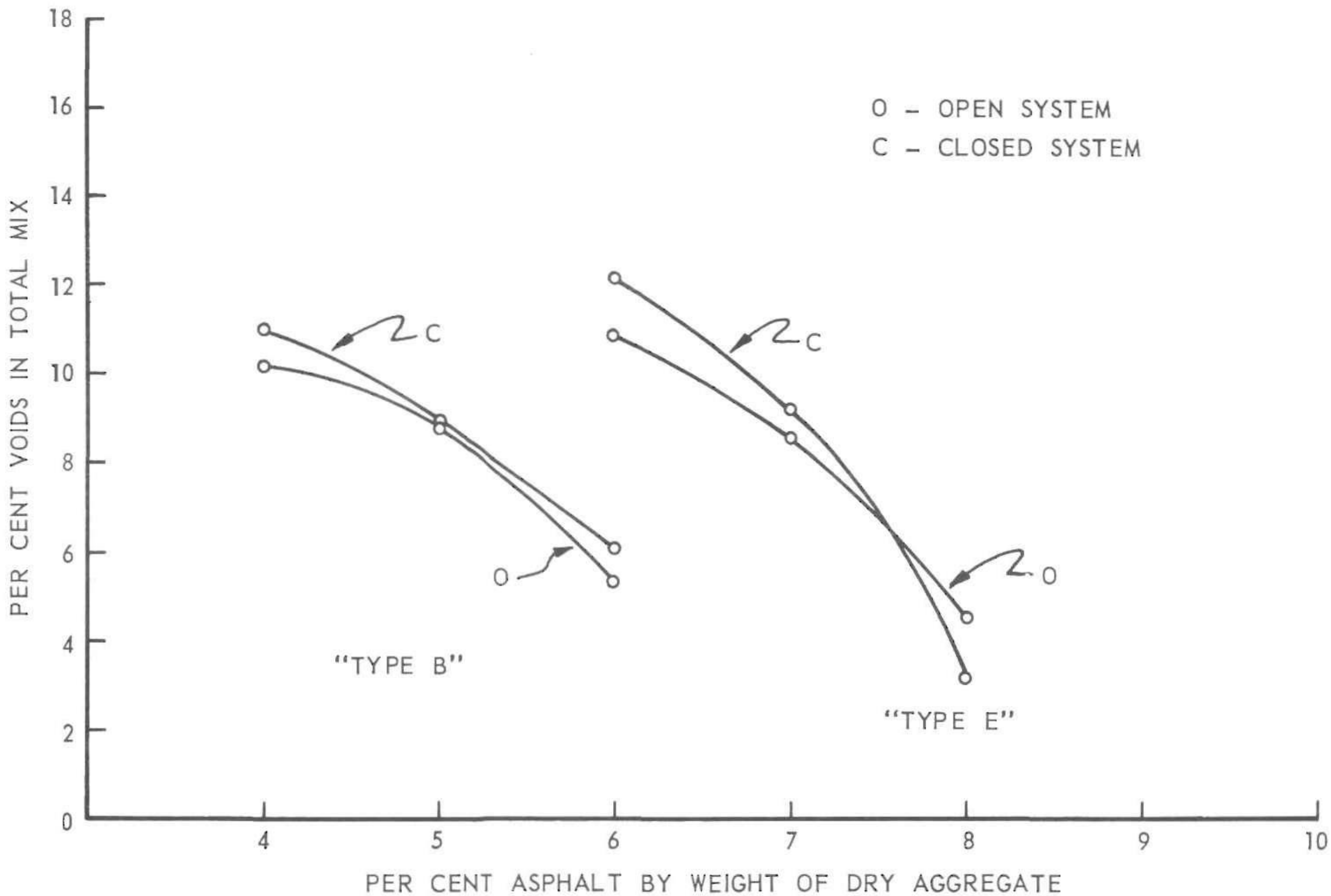

Figure 25. Percent Voids Total Mix Versus Percent Asphalt.

APPENDIX I

BATCH WEIGHTS

Table 6. Batch Weights for Asphalt Concrete Type E Surface Course

Screen Passed	Screen Retained	Batch Weights in Grams for Each % Asphalt		
		6	7	8
1/2	3/8	76.6	75.8	74.9
3/8	#4	880.9	871.7	862.3
#4	#8	574.5	568.5	562.4
#8	#16	536.2	530.6	524.9
#16	pan	1761.8	1743.4	1724.5
Total Weight of Aggregate		3830	3790	3749
Weight of AC-8		245	285	326
Total Weight of Sample		4075	4075	4075

Table 7. Batch Weights for Asphalt Concrete Type B Binder Course

Screen Passed	Screen Retained	Batch Weights in Grams for Each % Asphalt		
		4	5	6
1	3/4	81.8	80.9	80.0
3/4	1/2	981.6	971.3	961.0
1/2	3/8	572.6	566.6	560.6
3/8	#4	818.0	809.4	800.8
#4	#8	490.8	485.6	480.5
#8	#16	286.3	283.3	280.3
#16	pan	858.9	849.9	840.8
Total Weight of Aggregate		4090	4047	4004
Weight of AC-8		170	213	256
Total Weight of Sample		4260	4260	4260

APPENDIX II

BULK DENSITY AND VOIDS ANALYSIS PROCEDURE

<u>Formulas</u>.--The bulk densities of paraffin coated specimens were computed from the following formula:

$$Db = \frac{Wa}{Wac - Wwc - \frac{(Wac - Wa)}{Gp}} \quad (6)$$

where: Db = bulk density of coated specimen
Wa = weight of specimen (uncoated) in air, grams
Wac = weight of specimen plus paraffin coating in air, grams
Wwc = weight of specimen plus paraffin coating in water, grams
Gp = bulk specific gravity of paraffin

The bulk densities of the plain uncoated specimens were computed from the following formula:

$$Db = \frac{Wa}{Vb} = \frac{Wa}{Wa - Ww} \quad (7)$$

where: Db = bulk density of specimen
Vb = bulk volume of specimen
Wa = weight of specimen in air, grams
Ww = weight of specimen in water, grams

The maximum theoretical density was computed by knowing the per cent of asphalt and aggregate in each sample and the specific gravities of the asphalt (Gac) and aggregate (Gag).

It was computed from the following formula:

$$h = \frac{100}{\frac{\%\ AC}{Gac} + \frac{\%\ Agg.}{Gag}} \tag{8}$$

where: h = maximum theoretical density

The per cent of voids in the total mix was found by knowing the bulk density and maximum theoretical density of each sample. It was computed from the following formula:

$$n = 100 - \frac{100\ Db}{h} \tag{9}$$

where: n = per cent voids total mix
Db = bulk density
h = maximum theoretical density

The unit weight of the sample was computed from the following formula:

$$\text{Unit weight} = Db \times 62.4 \tag{10}$$

where: Db = bulk density of the specimen

For each different aggregate gradation and asphalt content there were twelve identical samples. Nine of these were used in the open system test and three were used in the closed system test. The results shown in Table 4 are averages of the nine open system tests and three closed system tests.

Sample Computation.--Specimen number thirty six.

$$Db = \frac{Wa}{Wa-Ww} = \frac{3958.7}{3958.7 - 2186.0} = \frac{3958.7}{1772.7} = 2.233 \ \frac{gms}{cc}$$

$$h = \frac{100}{\frac{\%\ AC}{Gac} + \frac{\%\ Agg}{Gag}} = \frac{100}{\frac{8}{1.025} + \frac{92}{2.629}} = 2.337 \ \frac{gms}{cc}$$

$$n = 100 - \left(\frac{100 \times 2.233}{2.337}\right) = 100 - 95.55 = 4.45\%$$

unit weight = 2.233 x 62.4 = 139.34 #/cf

APPENDIX III

OPEN SYSTEM CALCULATION PROCEDURE

Stress and Strain Calculation Procedure and Curves Procedure.--Simultaneous deformation dial and vertical load gauge readings were plotted on a set of coordinate axes similar to Figure 26. A curve was drawn through these points and was extended back to zero load to determine the dial reading at zero deformation. The dial reading at zero deformation was subtracted from each recorded dial reading to obtain the specimen's deformation and this was converted to strain by the following formula:

$$E = \frac{d}{H} \tag{11}$$

where: E = strain in inches per inch
d = deformation in inches
H = original height of specimen in inches

The specimen's end area was corrected for bulging according to the following formula:

$$A_1 = \frac{A}{1-E} \tag{12}$$

where: A_1 = new end area in square inches
A = original end area in square inches
E = strain in inches per inch

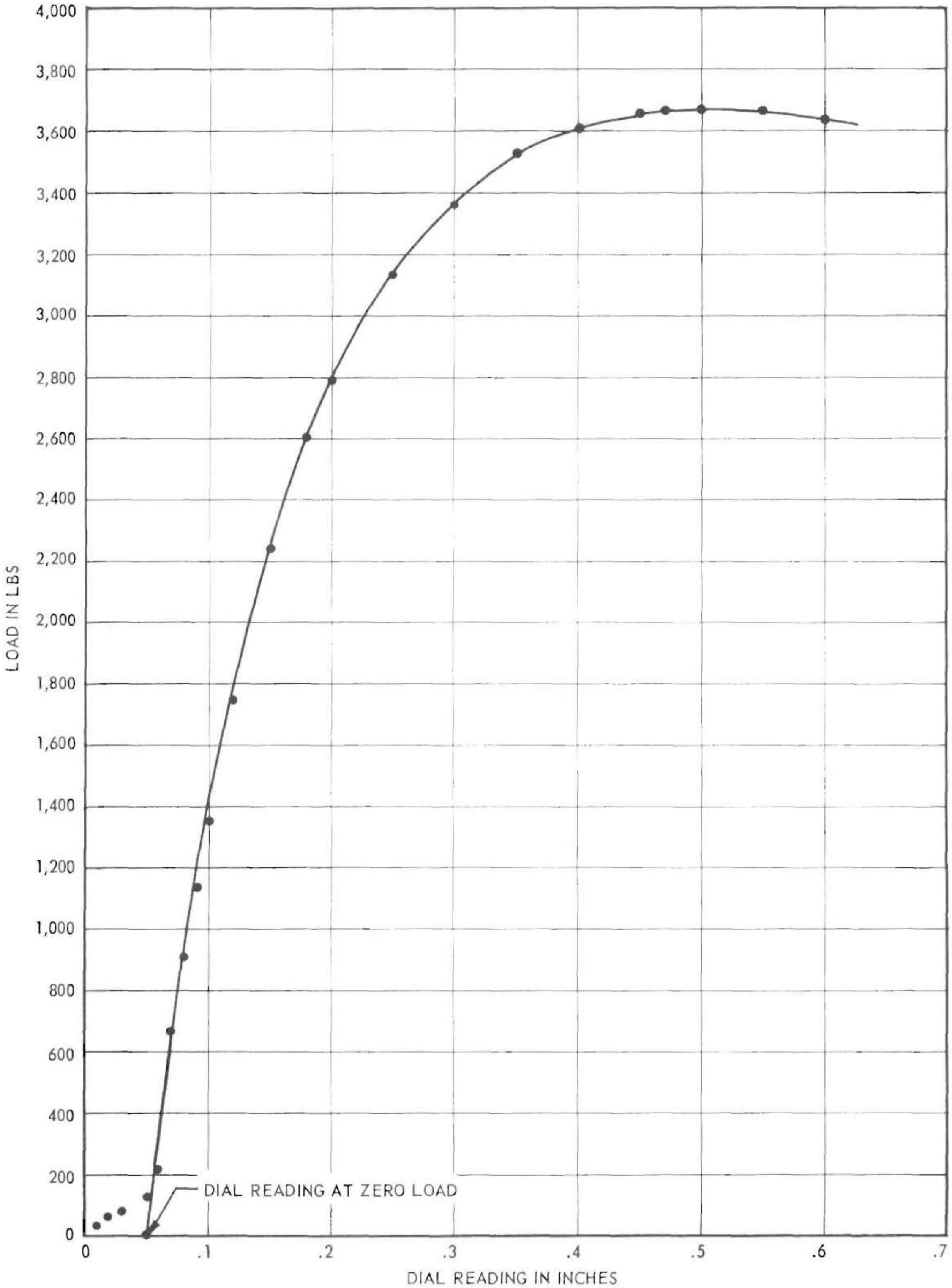

Figure 26. Vertical Load Versus Deformation Dial Curve for Sample No. 36.

The differential stress was computed by the following formula:

$$\sigma_1 - \sigma_3 = \frac{L}{A_1} \qquad (13)$$

where: $\sigma_1 - \sigma_3$ = differential stress in psi
L = load in pounds
A_1 = new end area of the specimen in inches'

The stress versus strain curves were then plotted on coordinate axes similar to Figure 27. The maximum differential stress was obtained from this figure. There were three identical samples for each mix having the same aggregate gradation, asphalt content, and lateral pressure. The data shown in Table 9 is an average of these three values.

Sample Computations.--Specimen number thirty six.

$$E = \frac{d}{H} = \frac{.42}{8.75} = .0480 \text{ inches per inch}$$

$$A_1 = \frac{A}{1-E} = \frac{12.56}{1 - .0480} = \frac{12.56}{.9520} = 13.19 \text{ sq. in.}$$

$$\sigma_1 - \sigma_3 = \frac{L}{A_1} = \frac{3670}{13.19} = 277.5 \text{ psi}$$

Calculation of Mohr Diagram Components.--The data in Table 9 having been previously calculated, three circles were drawn on a set of coordinate axes for each type mix. Each circle passed through a point of σ_3 distance to the right of the y-axis and had a diameter of $\sigma_1 - \sigma_3$. A line of best fit was

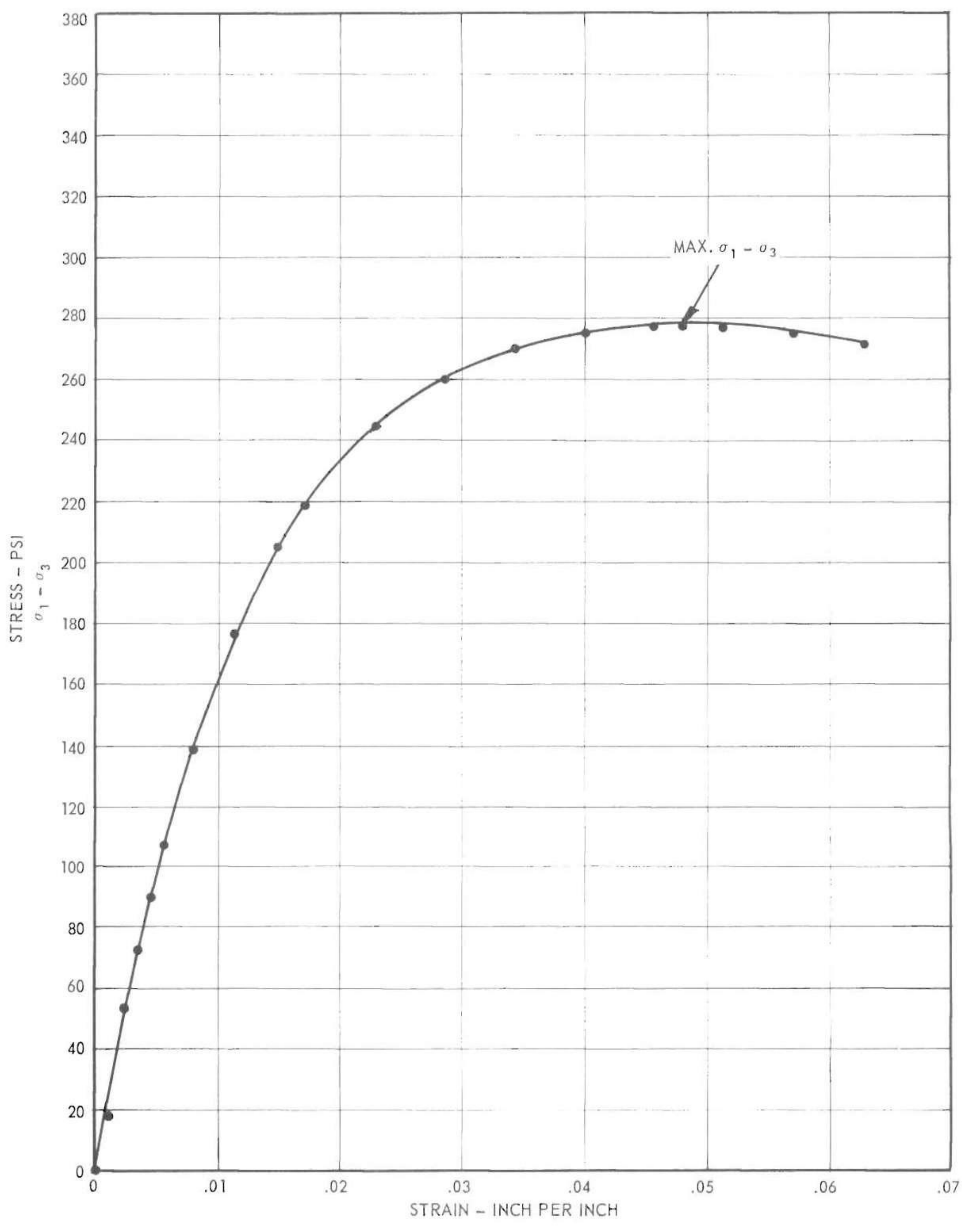

Figure 27. Stress Versus Strain Curve for Sample No. 36.

drawn tangent to the three circles and it was extended back until it intersected the y-axis.

The angle of internal friction is the slope of the tangent,and cohesion is value of the shear stress intercept. Values of Ø and c for each design mix are shown in Figures 28, 29, 30, 31, 32, and 33, and in Table 3.

Table 8. Calculated Stress and Strain Data for Sample #36

Load Dial #	Dial Reading In.	Center Dia. or Area Sq. In.	Deform. In.	Strain	Corr. Area Sq.In.	Stress psi
0	.00					
35	.01					
60	.02					
80	.03					
125	.05	12.56	.00	0	12.56	0
220	.06	12.56	.01	.0011	12.57	17.5
670	.07	12.56	.02	.0023	12.59	53.2
910	.08	12.56	.03	.0034	12.60	72.2
1135	.09	12.56	.04	.0046	12.62	89.9
1350	.10	12.56	.05	.0057	12.63	106.9
1750	.12	12.56	.07	.0080	12.66	138.2
2240	.15	12.56	.10	.0114	12.70	176.4
2605	.18	12.56	.13	.0149	12.75	204.3
2790	.20	12.56	.15	.0171	12.78	218.3
3135	.25	12.56	.20	.0229	12.85	244.0
3360	.30	12.56	.25	.0286	12.93	259.9
3525	.35	12.56	.30	.0343	13.01	270.9
3600	.40	12.56	.35	.0400	13.08	275.2
3650	.45	12.56	.40	.0457	13.16	277.4
3660	.47	12.56	.42	.0480	13.19	277.5
3670	.50	12.56	.45	.0514	13.24	277.1
3670	.55	12.56	.50	.0571	13.32	275.5
3640	.60	12.56	.55	.0629	13.40	271.6

Table 9. Stress Results

	σ_3 psi	$\sigma_1 - \sigma_3$ (average) psi
E-6	10	110.6
	30	184.4
	60	268.3
E-7	10	132.9
	30	198.1
	60	266.2
E-8	10	125.4
	30	207.7
	60	280.1
B-4	10	122.3
	30	194.7
	40	211.9
B-5	10	132.6
	20	163.3
	40	216.5
B-6	10	117.0
	20	155.1
	40	207.0

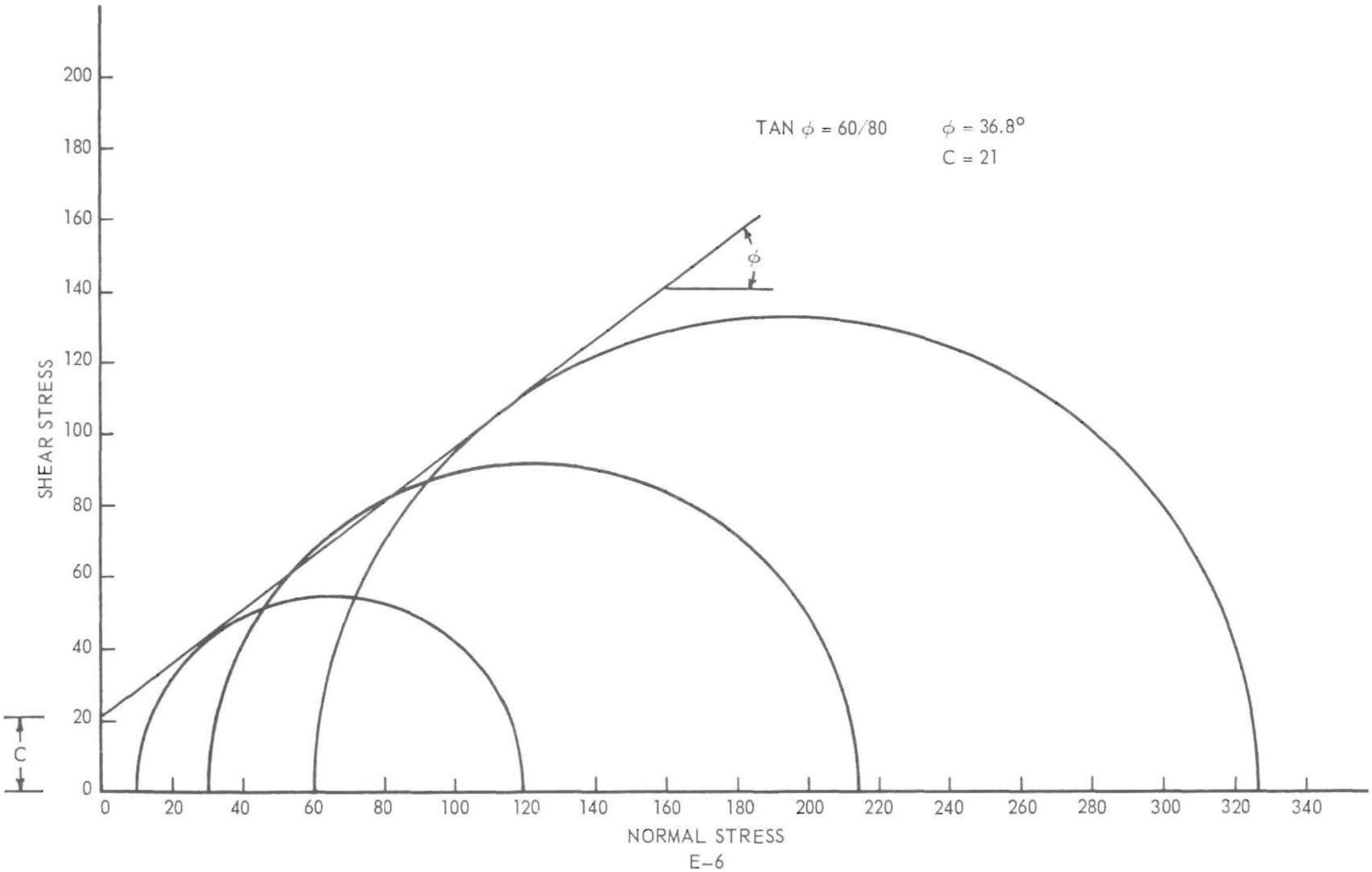

Figure 28. Mohr Rupture Envelope for an E-6 Mix.

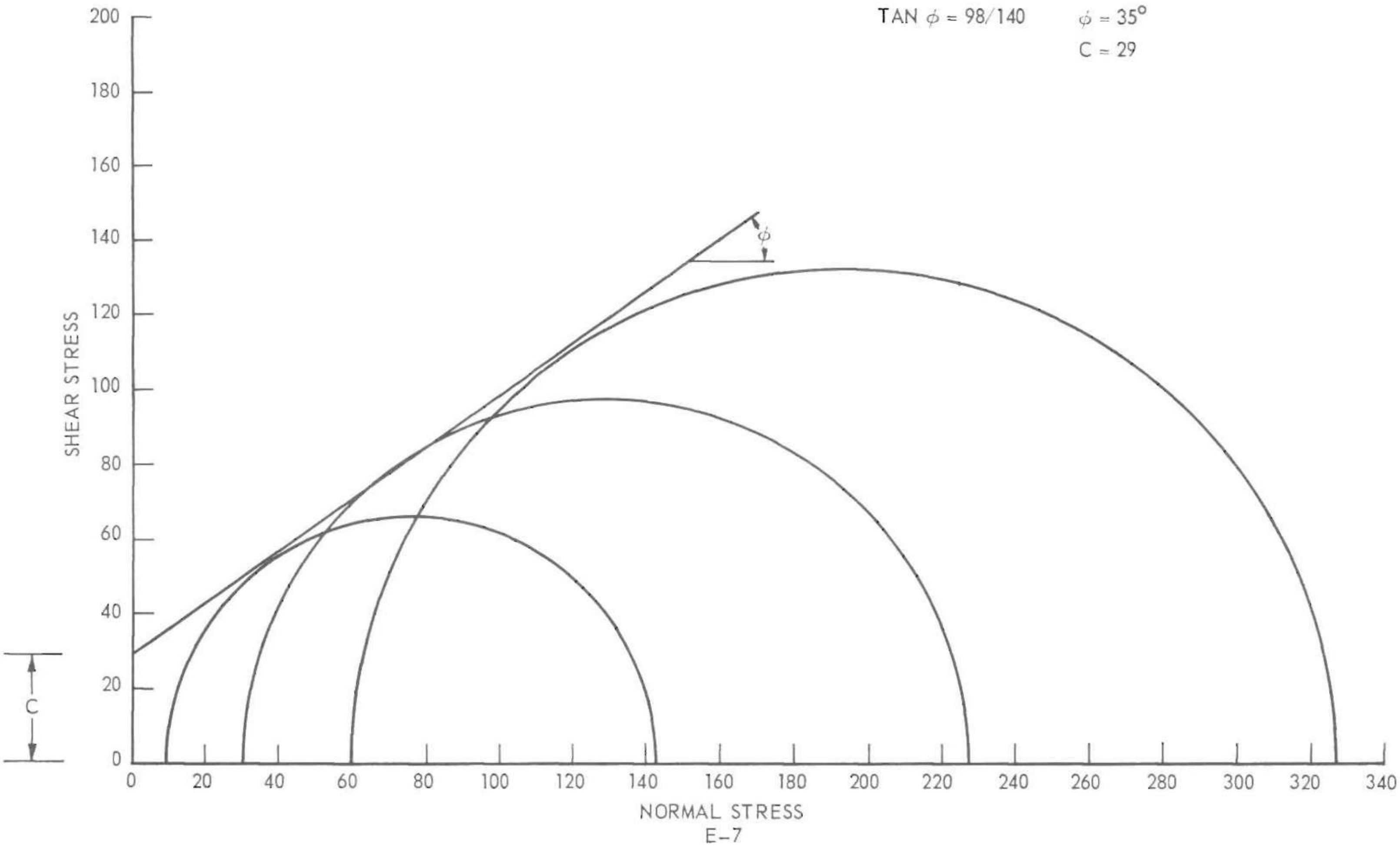

Figure 29. Mohr Rupture Envelope for an E-7 Mix.

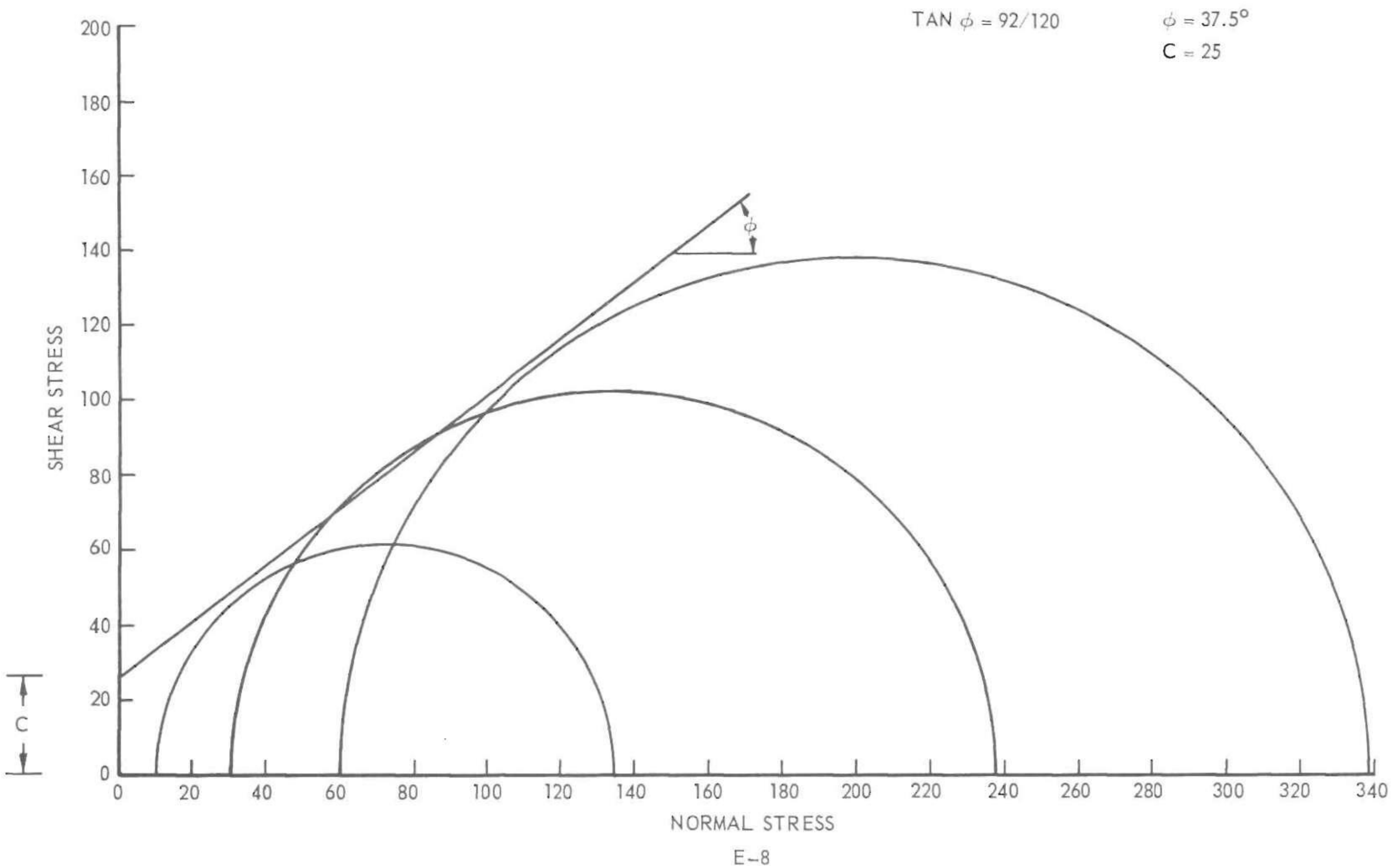

Figure 30. Mohr Rupture Envelope for an E-8 Mix.

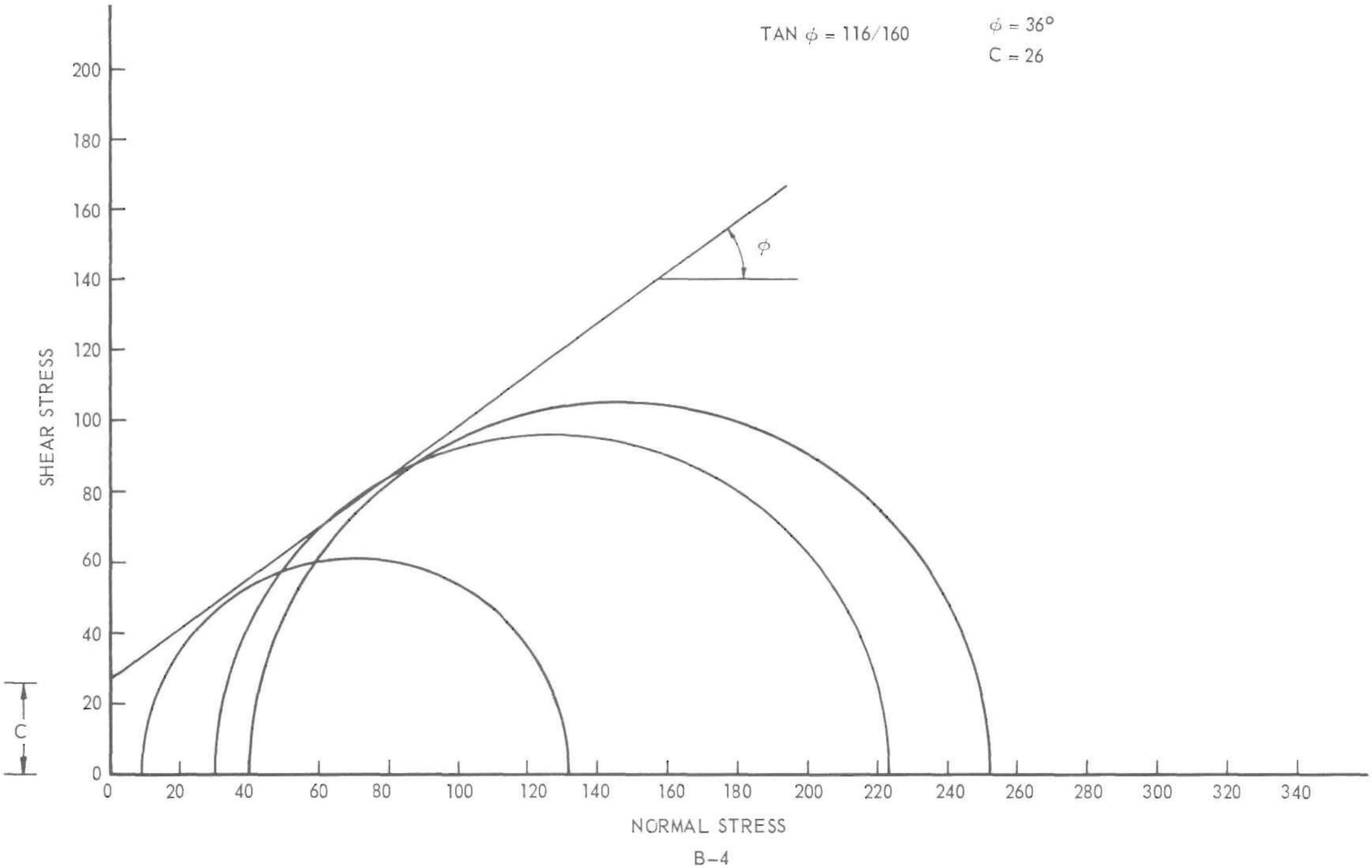

Figure 31. Mohr Rupture Envelope for a B-4 Mix.

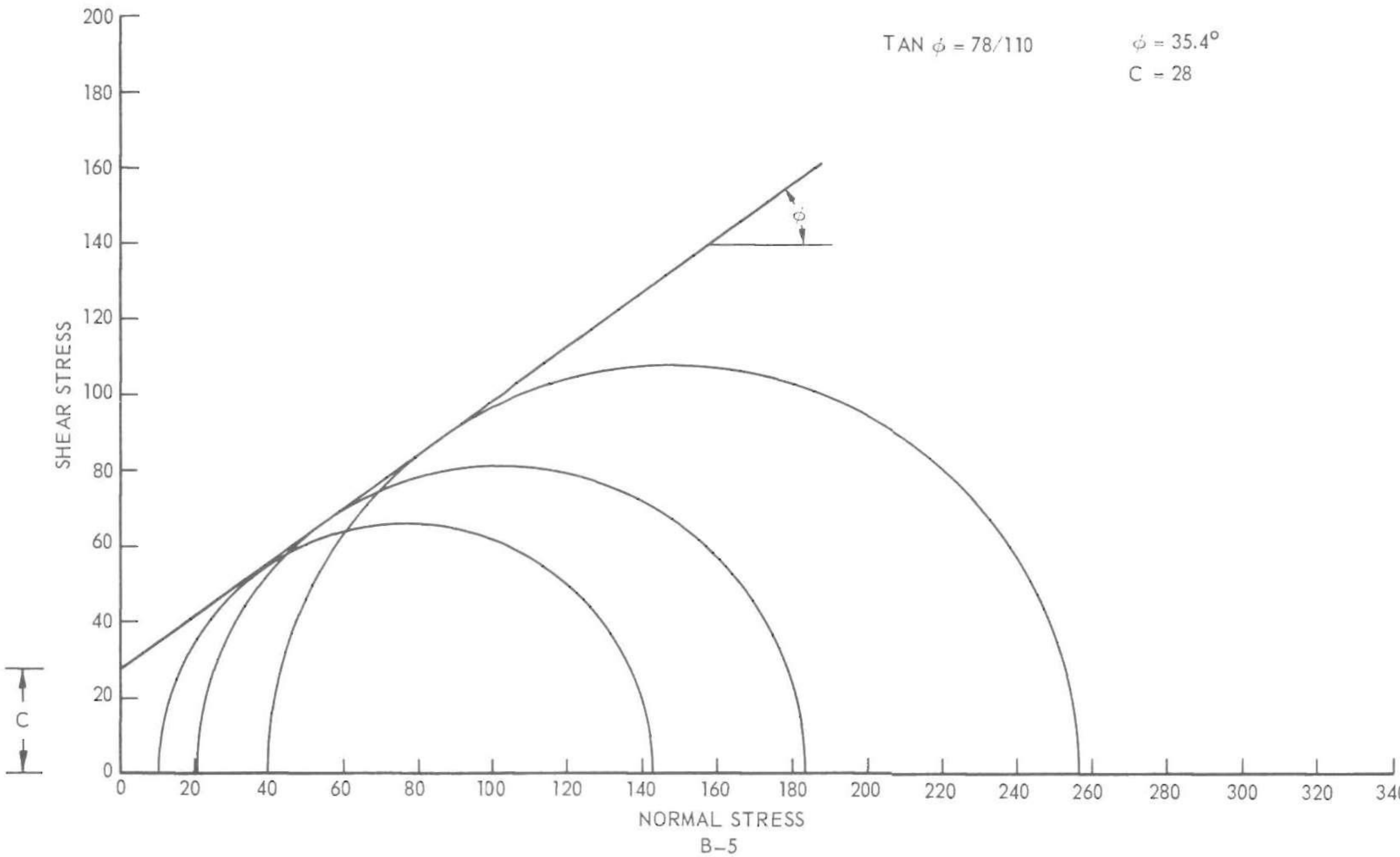

Figure 32. Mohr Rupture Envelope for a B-5 Mix.

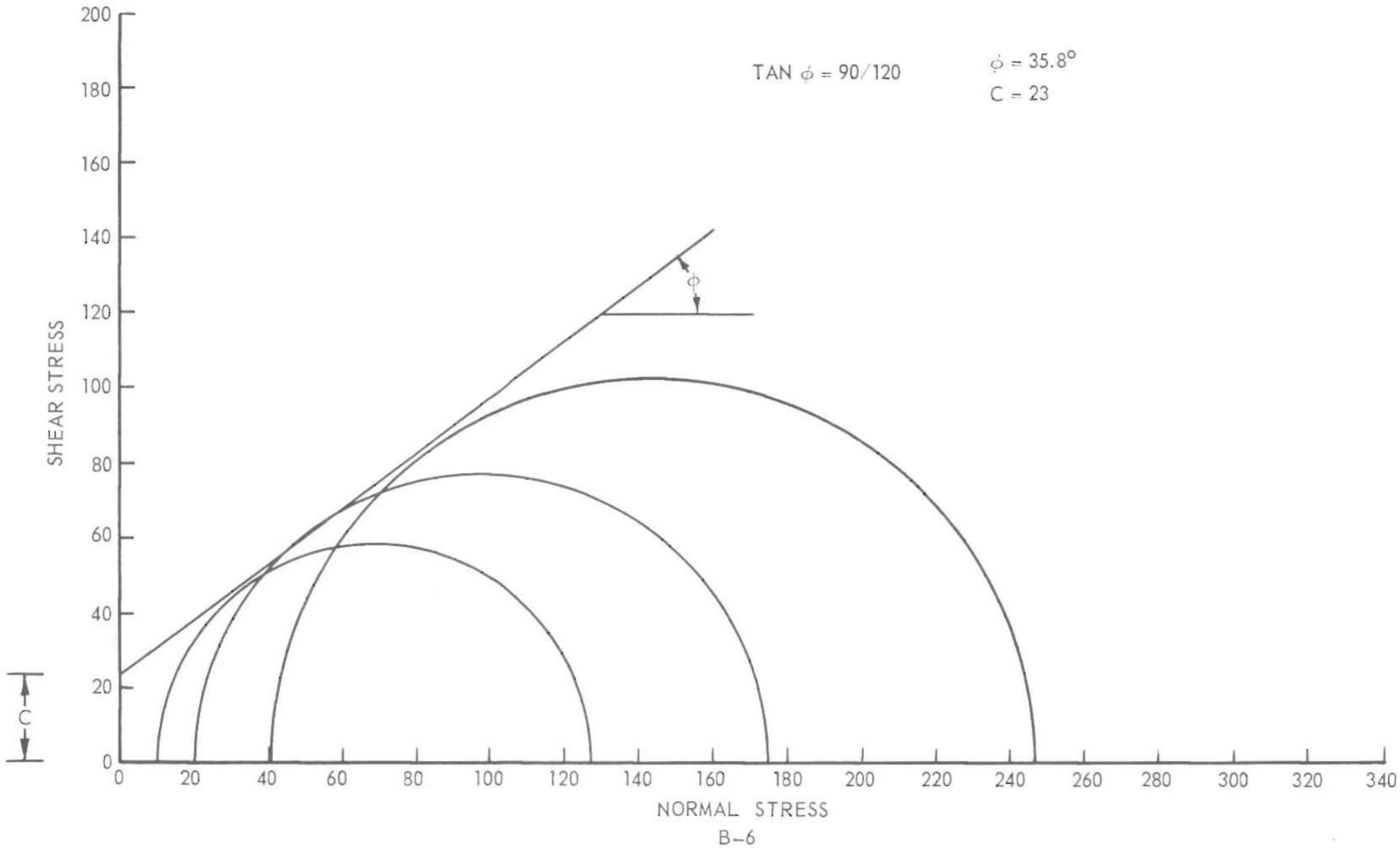

Figure 33. Mohr Rupture Envelope for a B-6 Mix.

APPENDIX IV

CLOSED SYSTEM CALCULATION PROCEDURE

Calculation of Mohr's Diagram Components.--Simultaneous readings of vertical load and lateral pressure were recorded. The vertical load was divided by the end area of the specimen (12.56 sq. in.) in order to obtain the vertical pressure. A vertical pressure versus lateral pressure curve was plotted similar to the one in Figure 34. A line was drawn tangent to the straight line portion of this curve and it was extended back until it intersected the y-axis. The angle of internal friction and cohesion were computed from equations two and five respectively. There were three identical samples for each mix of the same asphalt content and aggregate gradation. The results shown in Table 3 are averages of these three values.

Sample Calculations.--Specimen number fourteen. The values of a, b, and I were obtained from Figure 34.

$$\frac{A}{b} = \tan^2(45 + \emptyset/2)$$

$$A = \sigma_1 - \sigma_1' = 237$$

$$b = \sigma_3 - \sigma_3' = 80$$

$$2.963 = \tan^2(45 + \emptyset/2)$$

$$1.722 = \tan(45 + \phi/2)$$

$$59.9^{\circ} = 45 + \phi/2$$

$$14.9^{\circ} = \phi/2$$

$$\phi = 29.8^{\circ}$$

$$c = \frac{I}{2 \tan(45 + \phi/2)}$$

$$c = \frac{80}{3.444}$$

$$c = 23.2 \text{ psi}$$

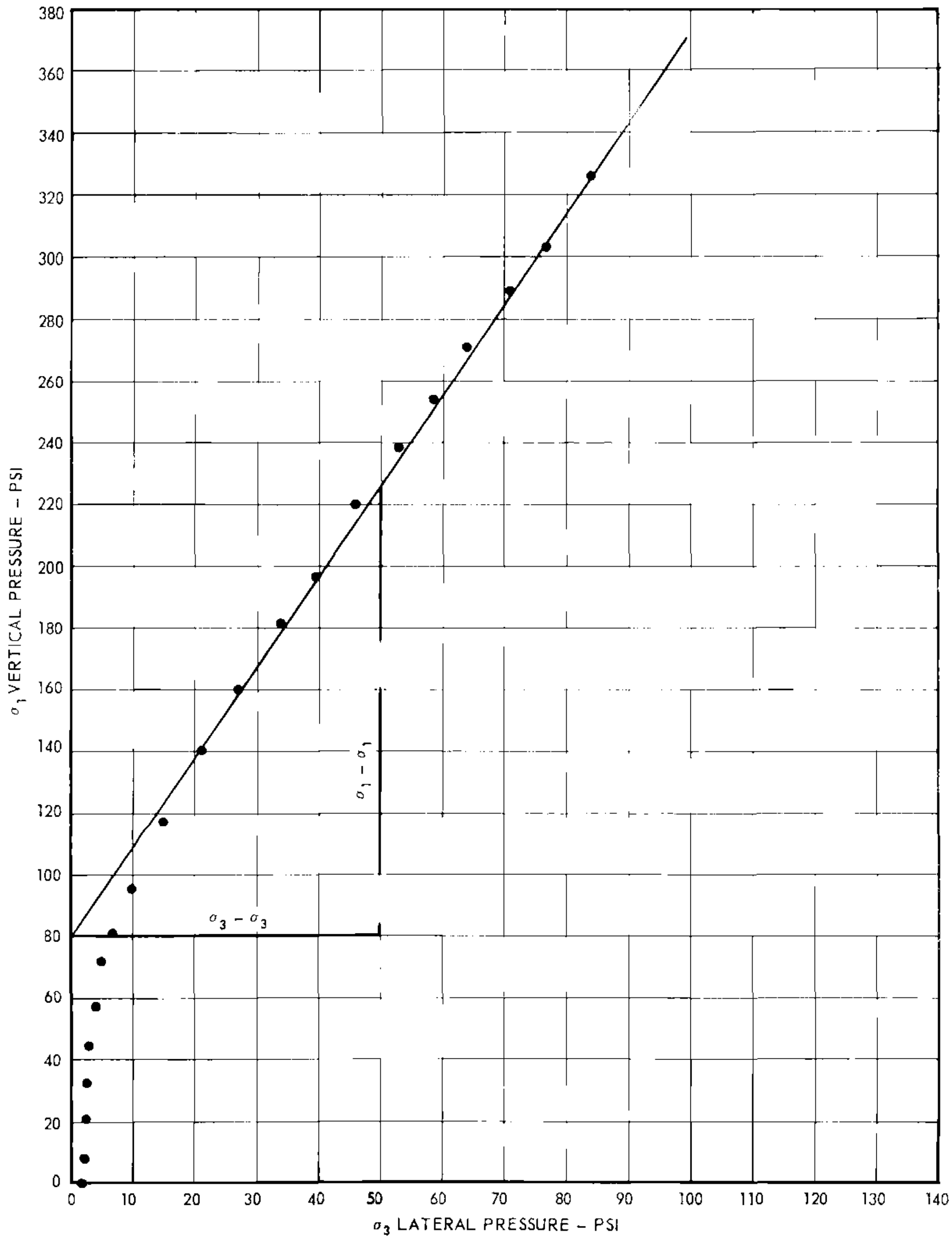

Figure 34. Vertical Pressure Versus Lateral Pressure Curve for Sample No. 14.

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